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FEASIBILITY OF BIOMASS BIODRYING FOR GASIFICATION PROCESS

ARASH HAMIDIAN

DÉPARTEMENT DE GÉNIE CHIMIQUE

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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présenté par : HAMIDIAN Arash

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M. TAVARES Jason-Robert, Ph. D., président

M. STUART Paul, Ph. D., membre et directeur de recherche

M. MAHMOOD Talat, Ph. D., membre externe

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RÉSUMÉ

L’un des défis importants de gazéification de biomasse est la limite de la qualité de matière première surtout la teneur en humidité qui joue un rôle significatif sur la performance de gazéification. La gazéification requise de faible niveaux d'humidité (20% et moins) et plusieurs rapports ont souligné l'humidité comme un problème typique de la gazéification de biomasse. L'humidité élevée affecte les taux de réactions qui ont lieu dans les gazéificateurs à la suite de chute de la température et qu’elle finalement augmente la teneur en goudron, diminue le rendement en gaz, change la composition du gaz produit et touche l'efficacité. Donc, il faut obligatoirement prétraiter la biomasse avant le gazéificateur et réduire la teneur en humidité au niveau approprié et économique. Les solutions connues sont soit séchage naturel (pas pratiquement possible pour les usines à l’échelle commerciales) ou des technologies classiques de séchage (couts d'opération élevés). Bioséchage est un procédé alternatif qui utilise à la fois convection de l’air et la chaleur dégagé par réactions biologiques comme la source d'énergie, afin de réduire l'humidité. Dans le réacteur de bioséchage chaleur est générée à partir de décomposition exothermique de la fraction organique de biomasse et c’est la raison pour laquelle ce processus est appelé " auto-chauffant ". Utilisant telle technologie pour sécher la biomasse au prétraitement d’un procédé de gazéification rends plusieurs avantages économiques et environnementaux aux usines.

En Europe, le bioséchage est utilisé pour traitement des déchets municipaux (MSW- Municipal Solid Waste) à l'échelle commerciale pour dégrader une partie de la portion biodégradable des déchets, afin de créer la chaleur et réduire la teneur en humidité pour générer le combustible solide récupéré (SFR- Solid Recovered Fuel). En Italie, l'industrie du vin a l’intention de développer le bioséchage pour la récupération de l'énergie des déchets de raisin après la fermentation et distillation, qui renvoie des avantages économiques énorme à l'industrie. Au Canada, le développement de cette technologie de séchage pour l'industrie des pâtes et papiers a été lancé à l'École polytechnique de Montréal comme une option pour des solutions de gestion des boues. Par conséquent, le réacteur discontinu a été développé en 2004 et ensuite le système continu (à l'échelle pilote) a été conçu en 2010 pour démontrer la faisabilité de bioséchage des boues mixte des usines des pâtes et papiers, pour la combustion efficace dans les chaudières. La

boue mixte a été séchée dans le réacteur jusqu'au 45% d'humidité, ce qui est le niveau approprié pour qu'il soit utilisé économiquement dans une chaudière. Analyse technico-économique a également révélé les potentiels des avantages économiques pour les usines des pâtes et papiers.

Cependant, des incertitudes concernant la faisabilité de bioséchage existait pour d'autres types de biomasse qui sont habituellement utilisés dans les procédés de gazéification, et la raison de ces incertitudes est principalement le faible niveau de nutriment disponible dans la matrice de biomasse ligno-cellulosique typique utilisé comme matière première. En outre, la viabilité économique de cette technologie en conjonction avec le procédé de gazéification à l'usine des pâtes et papiers avait été une question. Dans ce travail, la faisabilité de bioséchage de la biomasse en faible nutriment a été examinée par des expérimentations, et la modèle technico-économique a été élaboré afin de déterminer la performance de bioséchage à l'échelle commerciale. Dans l'analyse économique une approche globale pour estimation des couts de bioséchage a été introduite basé sur l'approche connue largement utilisée à l'industrie des procédés. Quelques sources de bénéfices ont aussi été identifiées.

ABSTRACT

An important challenge of biomass gasification is the limitation of feedstock quality especially the moisture content, which plays a significant role on the performance of gasification process. Gasification requires low moisture levels (20% and less) and several reports have emphasized on the moisture as a typical problem while gasifying biomass. Moisture affects overall reaction rates in the gasifiers as a result of temperature drop and ultimately increases tar content, decreases gas yield, changes the composition of produced gas and affects the efficiency. Therefore, it is mandatory to pre-treat the biomass before gasification and reduce the moisture content to the suitable and economic level. The well-known solutions are either natural drying (not practical for commercial plants) or conventional drying technologies (have high operating costs). Biodrying is an alternative process, which uses both convective air and heat of biological reactions as a source of energy, to reduce the moisture. In the biodrying reactor heat is generated from exothermic decomposition of organic fraction of biomass and that is why the process is called ‘’self-heating process’’. Employing such technology for drying biomass at pre-treatment units of gasification process returns several economic and environmental advantages to mills.

In Europe, municipal waste treatment (MSW) plants use the biodrying at commercial scale to degrade a part of the biodegradable fraction of waste to generate heat and reduce the moisture content for high quality SRF (Solid Recovered Fuel) production. In Italy, wine industry is seeking to develop biodrying for energy recovery of grape wastes after fermentation and distillation, which returns economic benefits to the industry. In Canada, the development of biodrying technology for pulp and paper industry was started at École polytechnique de Montréal as an option for sludge management solution. Therefore, batch biodrying reactor was successfully developed in 2004 and the pilot-scale continuous system was designed in 2010 to demonstrate the feasibility of mixed sludge biodrying for efficient combustion in biomass boilers. Mixed sludge was biodried in the reactor to 45% moisture level, which was the suitable level for boiler application. Techno-economic analysis also revealed the potential economic benefits for pulp and paper mills.

However, considerable uncertainties existed in terms of feasibility of the biodrying technology for other types of biomass that are usually used in the gasification process, mainly because of low nutrient level of typical lignocellulosic biomass used as feedstock. Furthermore, the technology had not been shown to be economically viable in conjunction with gasification process at pulp and paper mills. In this work the feasibility of low-nutrient biomass biodrying was tested by experiments and techno-economic model was developed to identify the performance of biodrying process for commercial-scale application. In the economic analysis, a comprehensive approach for biodrying cost assessment was introduced that is based on the well-known approach widely used in the process industry and few sources of benefits were identified.

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ASU	Air Separation Unit
BFB	Bubbling Fluidized Bed
BOD	Biological Oxygen Demand
CFB	Circulated Fluidized Bed
CTC	Carbon Trim Cell
DCF	Discounted Cash Flow
DFB	Dual Fluidized Bed
FCI	Fixed Capital Investment
FB	Fluidized Bed
HCP	Heat Carrier Particle
HHV	Higher Heating Value
IRR	Internal Rate of Return
LHV	Lower Heating Value
MBT	Mechanical-Biological Treatment
MSW	Municipal Solid Waste
NCV	Net Calorific Value
NPV	Net Present Value
Nu	Nusselt number
OPEX	Operating Expenses
PBP	Payback Period
PC	Purchased Cost
RDF	Refused Derived Fuel
RH	Relative Humidity
RST	Rotary Sludge Thickener
SRF	Solid Recovered Fuel
TDC	Total Direct Cost
TGA	Thermo Gravimetric Analysis
TRI	ThermoChem Recovery International
WAS	Waste Activated Sludge

Chapter 1 : Introduction

1.1. Context

One of the significant challenges of biomass gasification compared to combustion is limitation in quality of feedstock especially in terms of moisture content (Fagernäs, Brammer, Wilén, Lauer, & Verhoeff, 2010; J. Xu & Qiao, 2012), which plays an important role in gasification performance. Combustion boilers can tolerate higher moisture contents in the cost of reduced energy efficiency (Pang) whereas gasification process requires low moisture levels. Several reports have highlighted the moisture content as a typical problem while gasifying biomass (McKendry, 2002). Fresh biomass has in average 30-60% moisture that is not appropriate for gasification.

Moisture content of biomass has impact on the gasification process and mainly reduces overall reaction rates as a result of temperature drop. Moisture affects the drying and subsequent de-volatilization and gasification stages. Evolution of volatile gases in de-volatilization stage is basically a two-step process: first biomass yields tar, primary volatile gases (CO, H_2, CH_4, etc.) and residual char in the pyrolysis zone, and in the second step the tar is cracked at elevated temperatures and transformed to secondary volatile gases ($C_nH_x \leftrightarrow nC + (x/2)H_2$ & $C_nH_x + mH_2O \leftrightarrow nCO + (m + x/2)H_2$) (Ian Narvaez, 1996; Javier Gil, 1997; J. Xu & Qiao, 2012). Besides, hydrogen and carbon monoxide are produced from some gasification reactions such as Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$), steam-carbon reaction ($C + H_2O \leftrightarrow CO + H_2$), and methane reforming reaction ($CH_4 + H_2O \leftrightarrow 3H_2 + CO$), which are highly endothermic. Higher moisture content in biomass absorbs more heat for evaporation and drops the gas and particle temperatures (McKendry, 2002; J. Xu & Qiao, 2012), which lowers the de-volatilization rate and shifts the equilibrium of the endothermic gasification reactions toward the formation of carbon dioxide and water. Therefore, moisture ultimately affects the last stage of gasification that results tar content increase (Ian Narvaez, 1996; Javier Gil, 1997), gas yield decrease (Kaewluan & Pipatmanomai, 2011), gas composition change (Javier Gil, 1997; Lv et al., 2004) and the efficiency of gasifier is ultimately affected (Kaewluan & Pipatmanomai, 2011). Schuster et. al. have mathematically modeled steam gasification in dual fluidized beds and reported zero gasifier

efficiency at 66% biomass moisture content (G. Schuster, 2001), and in an experimental work Kaewluan et. al. have gasified rubber woodchips of different moisture contents in a small fluidized bed gasifier and reported significant operational difficulties at moisture level higher than 30%, as well as approximately 10% efficiency decrease while increasing moisture content by about 15% (Kaewluan & Pipatmanomai, 2011).

Therefore, it is necessary to treat biomass moisture and decrease it to the appropriate and economic level at pre-treatment units. Solutions for high moisture content biomass are natural drying technique or conventional drying technologies. For commercial scale plants the natural drying is not practical because it requires extensive lands and also the sunlight is limited in many regions during the year. On the other side, the conventional drying techniques bear high operating cost if there would be no or expensive heating source in the plant (Kaewluan & Pipatmanomai, 2011).

Biodrying (biological drying) is an alternative process to conventional thermal drying that employs convective air as well as heat of biological reactions to reduce the moisture level of biomass. It is believed that employing biodrying for biomass pre-treatment in gasification process returns several economic and environmental advantages that have created encouragement for this study.

The term “biodrying” had primarily been used by Jewell et. al. (1984) while reporting operating parameters of daily manure’s drying (He, Zhao, Zheng, Wu, & Shao, 2013). However, the mechanism of biodrying is similar to composting where biological activity and aerobic decomposition of organic fraction takes place but their objectives and final products are different. The objective of composting is to stabilize the organic matter of raw wastes, reduce odors, and kill the pathogenic organisms to produce uniform organic fertilizer for land application whereas in the biodrying the goal is to reduce the moisture content of biomass for further applications such as energy recovery or etc. (Haga, 1999). Three main current applications of biodrying include: Municipal Solid Waste (MSW) treatment, grape waste treatment in wine industry, and moisture removal of mixed sludge at pulp and paper mills (Ken M. Frei, Cameron, & Stuart, 2004; Elena Cristina Rada & Ragazzi, 2012; E. C. Rada et al., 2010). The first one has been

practiced since more than a decade ago in Europe as a part of MBT (Mechanical-Biological Treatment) technologies with 20 commercial references (Velis, Longhurst, Drew, Smith, & Pollard, 2009), whereas the two latters are potential applications still under development (Elena Cristina Rada & Ragazzi, 2012; E. C. Rada, Ragazzi, Fiori, & Antolini, 2009; Shahram Navaee-Ardeh, 2006).

In MSW treatment plants, waste stream is transformed to SRF (Solid Recovered Fuel) for waste-to-energy options instead of landfilling. In such units, the entire MSW stream enters to biological process where biodrying degrades a part of the biodegradable organic fraction of the waste and generates heat to evaporate moisture content, which results high heating value SRF comparable to brown coal, when fine fraction such as ash, glass and stones are removed (Tambone, Scaglia, Scotti, & Adani, 2011). Some commercial biodrying technology providers for MBT application are Eco-deco, Entsorga, Herhof, Nehlsen, Wehrle Werk (Velis et al., 2009).

Valorization of grape waste through energy recovery is an option for wine industry to make economic and environmental benefits. The industry consumes 1.3 kg grape to produce a liter of wine where 20% are wasted after fermentation and distillation. Therefore, application of biodrying process for evaporation of water content and transforming the grape waste to SRF of different quality suitable for energy recovery has grabbed the attentions (Elena Cristina Rada & Ragazzi, 2012; E. C. Rada et al., 2009).

Development of biodrying technology for pulp & paper industry was started at École polytechnique de Montréal in 2004 and widely studied since then. It had primarily been reported as the most cost effective option among different emerging sludge management options at pulp & paper mills to increase the dryness level of sludge for boiler application (K.M. Frei, 2006). To address this issue, batch biodrying reactor system was developed at Polytechnique de Montréal in 2004 whose goal was to increase the dryness level of mixed sludge for efficient combustion in boilers (Ken M. Frei et al., 2004). Successful test results and $2 million per year operating costs saving estimation were the driving forces to develop continuous biodrying technology. Improved controllability and potentials of establishment in crowded pulp and paper sites were also identified as advantages of continuous technology over batch system (Shahram Navaee-Ardeh,

2006). In 2010, Navaee-Ardeh et. al. developed the mathematical model of continuous system and designed vertical pilot scale reactor in which mixed sludge was dried to 55%, the appropriate level for efficient combustion in boiler (Shahram Navaee-Ardeh, 2010).

Previous studies on the biodrying were successful, which encouraged continuing the research and investigations of the novel technology for gasification-based biorefinery process at pulp and paper mills. Such application addresses two major problems in the mill, which will be discussed briefly in the coming sections: first, it dries the biomass in the pre-treatment units, and second, it resolves the sludge management problem in the mill. Recently, ThermoChem Recovery Corp. successfully constructed and commissioned a small process demonstration gasification unit in the United States, which could process 4 tons per day of biomass (Newport et al., 2012), then they successfully established a commercial scale process with the partnership of NewPage Inc. (a pulp and paper mill). The novel biodrying process –in case of successful development for gasification application- can be employed at the pre-treatment of such mill.

Chapter 2 : Literature review

2.1. Principles of drying of solids (Warren L. McCabe, 2005)

Drying means reducing the moisture content from initial value to some acceptable final value. Drying of a solid is removing a portion of water content (or other liquids) from solid material to reduce it to the acceptable level appropriate for subsequent application. There are two possibilities for water removal from a solid: mechanically by presses or centrifuges or thermally by vaporization. Mechanical de-watering is cheaper than thermal drying therefore it is usually recommended to remove the water mechanically, as much as possible before feeding the solid materials to thermal dryers. Thermal drying is often complicated by diffusion in the solid but it is possible to dry it by heating at merely above the boiling point of water (or other liquids). However, thermal damage of the solid phase in such temperature must be analyzed prior to any design. Solid materials to be dried might be in different forms such as granule, flakes, crystal, powder, slabs or sheets and water to be removed might be at the surface of the solids, totally inside the solid or partly inside and partly outside of the solids.

2.1.1. Classifications of conventional dryers

There are several types of dryers: continuous and batch, agitated and un-agitated, vacuum and atmospheric dryers that complicate the classification of dryers. However, the most common classification divides the conventional dryers into three groups:

- Direct (or adiabatic) dryers: where solids are directly exposed to a hot gas
- Indirect or non-adiabatic dryers: where heat is indirectly transferred to solids through an external medium such as steam
- Dryers heated by dielectric, radiant or microwave energy

2.1.2. Principles of drying

2.1.2.1. Cross-circulation and through-circulation dryings of solids

Cross-circulation drying is the drying of a bed of wet solids over which the air passes across the surface and the drying happens on the sides of the solid. Here the gas is blown across the surface of a bed or slab of solids or across one or both faces of a continuous sheet (Figure 2.1). Such drying has slow drying rate and it depends on the distance liquid moves to reach the surface of

the solid. If solid particles are large enough the air passes through the bed instead of across it and significantly increases the drying rate. This is called through-circulation drying (Figure 2.2).

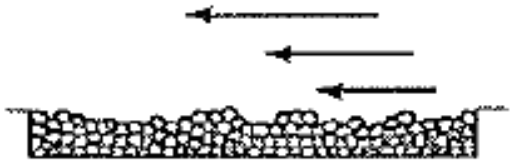


Figure 2.1. Cross-circulation drying (Warren L. McCabe, 1993)

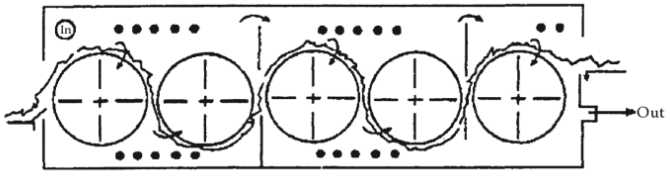


Figure 2.2. Through-circulation drying [adapted from (Mujumdar, 2015)]

2.1.2.2. Temperature patterns in the dryers

Temperature variations in a dryer depends on the: nature of feedstock, water content of feedstock, temperature of heating medium, allowable final temperature of solid, drying time, etc. However, pattern of temperature variation in conventional technologies are similar from one to another, which has been depicted in Figure 2.3. In an ideal continuous dryer, temperature of wet solids rises quickly from initial value (T_{sa}) to vaporization temperature (T_v) that is the boiling point of water at dryer's pressure. Drying continues in T_v for a considerable time but normally after a short period of time the temperature of solid slightly rises as a zone of dry solid appears on the surface of solid particles. Close to gas inlet (right side of the graph), in a relatively small length of the dryer temperature of the solid rapidly rises to higher than vaporization temperature (T_{sb}). This is due to the fact that energy required to heat up the dry solid is small compared to energy required for vaporization. Therefore for heat-sensitive solids the dryer must be designed in a way to keep the outlet temperature (T_{sb}) close to the vaporization temperature (T_v). At steady state the temperature at any given point in the dryer is constant but it varies along the length of the dryer.

Gas temperature profile is more complex due to variation of temperature driving force and overall heat transfer coefficient along the length of the dyer.

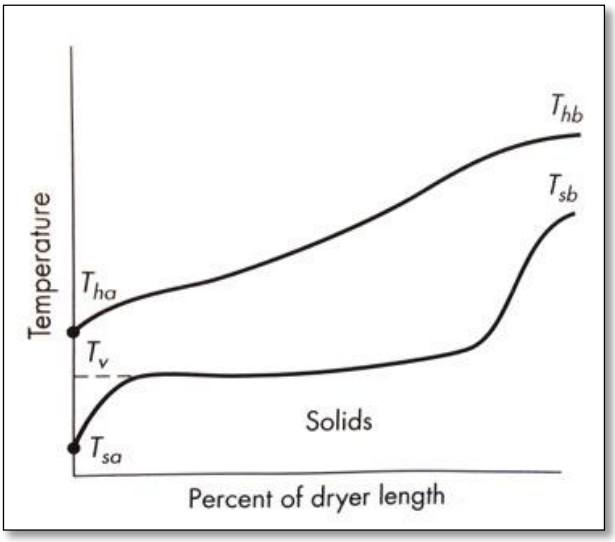


Figure 2.3. Temperature pattern in countercurrent conventional dryers

(Warren L. McCabe, 2005)

2.1.2.3. Phase equilibrium and moisture concentration

When wet solid comes in contact with air of lower humidity than moisture of the solid, the solid tends to lose moisture and dry up to equilibrium with air (mass diffusion of water) due to concentration gradient. If the air would be more humid than solid then solid adsorbs the moisture until equilibrium is gained. Concentration of fluids is expressed as mole fraction that is meaningless for wet solids therefore mass of water per unit mass of dry solid represents the concentration of water (Eq. 2.1) (Warren L. McCabe, 2005).

$$X_{(water)} = \frac{m_{(water)}}{m_{(dry\ solid)}} \qquad (2.1)$$

2.1.2.5. Heat duty in the dryers

Heat is used for the following items in a conventional dryer:

- To heat the solid and liquid feed to vaporization temperature
- To vaporize the liquid
- To heat the solid to the final temperature

- To heat the vapor to the final temperature
- To heat the air or other additional gases to their final temperature

Therefore, necessary heat to be transferred in the dryer is written as Eq. 2.3- 2.7, where indices 1 and 2 represent initial and final conditions and indices L, s, v represent solid, liquid and vapor.

$$Q_{total} = m_s.C_{P_{(s)}}.\left(T_{vaporization} - T_{s_1}\right) + m_{(L)}.C_{P_{(L)}}.\left(T_{vaporization} - T_{L_1}\right) + \left(m_{L_1} - m_{L_2}\right).h_{laten} + m_s.C_{P_s}.\left(T_{s_2} - T_{vaporization}\right) + \left(m_{L_1} - m_{L_2}\right).C_{P_{(v)}}.\left(T_{v_2} - T_{vaporization}\right) \quad (2.3)$$

Where $T_{vaporization}$ is the boiling point of liquid, m_s is the dry mass of solid and m_L is the mass of liquid in dry solid. By defining liquid concentrations as mass of liquid per mass of dry solid (Eq. 2.4 and 2.5), the quantity of heat per unit mass of dry solid is re-formulated as Eq. 2.6.

$$\frac{m_{L_1}}{m_s} = X_1 \quad (2.4)$$

$$\frac{m_{L_2}}{m_s} = X_2 \quad (2.5)$$

$$\frac{Q_{total}}{m_s} = C_{P_{(s)}}.\left(T_{vaporization} - T_{s_1}\right) + X_1.C_{P_{(L)}}.\left(T_{vaporization} - T_{L_1}\right) + \left(X_1 - X_2\right).h_{latent} + C_{P_{(s)}}.\left(T_{s_2} - T_{vaporization}\right) + \left(X_1 - X_2\right).C_{P_{(v)}}.\left(T_{v_2} - T_{vaporization}\right) \quad (2.6)$$

Initial temperature of the liquid is equal to initial temperature of solid, so by re-arranging the Eq. 2.6 total quantity of necessary heat per unit dry mass of solid can be obtained from Eq. 2.7 where C_P is the average in the temperature range of initial to final levels.

$$\frac{Q_{total}}{m_s} = C_{P_{(s)}}\left(T_{s_2} - T_{s_1}\right) + X_1.C_{P_{(L)}}\left(T_{vaporization} - T_{s_1}\right) + \left(X_1 - X_2\right).h_{latent} + \left(X_1 - X_2\right).C_{P_{(v)}}.\left(T_{v_2} - T_{vaporization}\right) \quad (2.7)$$

In adiabatic dryers, total heat of Eq. 2.7 comes from cooling of a gas (an external source), so the required temperature of gas can be obtained from Eq. 2.8 where m_g is mass rate of dry gas and h_g is humid heat capacity of gas at inlet humidity.

$$Q_{total} = m_g . h_g . (T_{h_2} - T_{h_1}) \quad (2.8)$$

2.1.2.6. Drying rates and critical moisture contents

Moisture of wet solid decreases over time. The drying rate is defined as quantity of the moisture removed from solid per unit of time per unit area of the solids (Eq. 2.9).

$$R = -\frac{dm_v}{A\,dt} = -\frac{m_s}{A}\frac{dX}{dt} \quad (2.9)$$

Where m_v is liquid content, m_s is mass of dry solid, A is the unit area of drying, t is the drying time and X is the liquid concentration that is defined as mass of liquid per mass of dry solid. In the drying processes there are two drying rate periods:

i. *Constant-rate period*: where the rate is constant (or decreases slightly) during considerable period of time
ii. *Falling-rate period*: where drying rate is decreased linearly, in polynomial shape, or other curve types.

During the constant rate period the solid is too wet and a continuous liquid film is formed on its surface to guarantee a consistent evaporation. Enough liquid on the surface behaves like there is no solid. As moisture content decreases, the constant-rate period is terminated at a point called ‘’critical point’’ where there is not sufficient water on the surface to form the continuous liquid film (Warren L. McCabe, 1993). Figure 2.4 is the example of drying rate periods for (a) a bed of glass beads containing water and n-butanol (b) porous ceramic plate containing water. Drying rate of the glass of beads up to about 25% moisture content is referred as constant-rate period although it decreases a little bit, then falling-rate period is observed. Ceramic plate is an example of solid with two falling-rate periods. The drying up to the point B is in constant-rate period

and then it faces two falling rate periods: the first falling-rate period is linear up to the point C and the second has curve shape up to the end (point D).

The point(s) where constant-rate period ends is called “critical moisture content”. It is the point below which enough liquid cannot be transferred from the interior of solid to the surface to keep the continuous liquid film. Critical moisture level depends on several parameters such as drying conditions, the material of solid, heat and mass resistance of the solid and etc. If initial moisture content would be less than critical level no constant-rate period is experienced. Sometimes critical points can be clearly identified and sometimes approximation is required (like glass beads).

If solid would be too wet that a continuous liquid film appears on the external surface, evaporation will be the same as a pool of liquid and true constant-rate period is expected to take place (AB in Figure 2.4-b). No slight decreases will appear, the surface temperature is the same as wet bulb temperature and heat transfer by radiation or conduction is negligible. This true constant-rate period is maintained only if there would be a mechanism to bring the interior water of solid to the surface fast enough to always keep the surface wet. In such cases the period is called “prolonged constant-rate period” and the calculations of regular constant-rate period applies to it.

During the constant-rate period temperature of the interface (T_i) is assumed equal to wet bulb temperature (T_{wb}) and drying rate can be estimated by Eq. 2.10 that is based on the heat transfer. For determining the heat transfer coefficient, estimations based on the empirical equations can be made. For turbulent gas flow parallel to solid surface Eq. 2.11 and gas flow perpendicular to solid surface with velocity of 0.9-4.5 m/s Eq. 2.12 have been recommended (Warren L. McCabe, 2005).

$$R_{constant-rate\ period} = \frac{[\, h_y(T-T_i)\,]}{\lambda_i} \tag{2.10}$$

$$Nu = \frac{h_y\, D_e}{k} = 0.037\, Re^{0.8}\, Pr^{0.33} \tag{2.11}$$

$$h_y = 24.2\, G^{0.37} = 24.2\, (\rho.u)^{0.37} \qquad (2.12)$$

In these equations $R_{constant\text{-}rate}$ is constant drying rate per unit area, h_y is heat transfer coefficient of the gas, T is temperature of the gas (dry-bulb temperature if air is used), T_i is temperature of interface, λ_i is latent heat of liquid at interface temperature, Nu is Nusselt number, k is thermal conductivity at mean film temperature, G is mass velocity of gas in lb/hr.ft^2, ρ is gas density in lb/ft^3 and u is gas velocity in ft/hr.

In the falling-rate period diffusion of moisture to the surface of solid particles limits the drying rate. Moisture moves through the pores of the solids by capillarity and to some extend by surface diffusion.

2.1.2.7. Drying time

Drying time is the integration of Eq. 2.9 between first and second moisture levels that can be re-written as Eq. 2.13.

$$t_{Total} = \int_{t_1}^{t_2} dt = \frac{m_s}{A} \int_{X_2}^{X_1} \frac{dX}{R} \qquad (2.13)$$

If drying happens only in the constant-rate period the rate is obtained from Eq. 2.10-2.12 and drying time is calculated as Eq. 2.14.

$$t_{constant-rate\ period} = \frac{m_s(X_1 - X_2)}{A.R_{constant-rate}} \qquad (2.14)$$

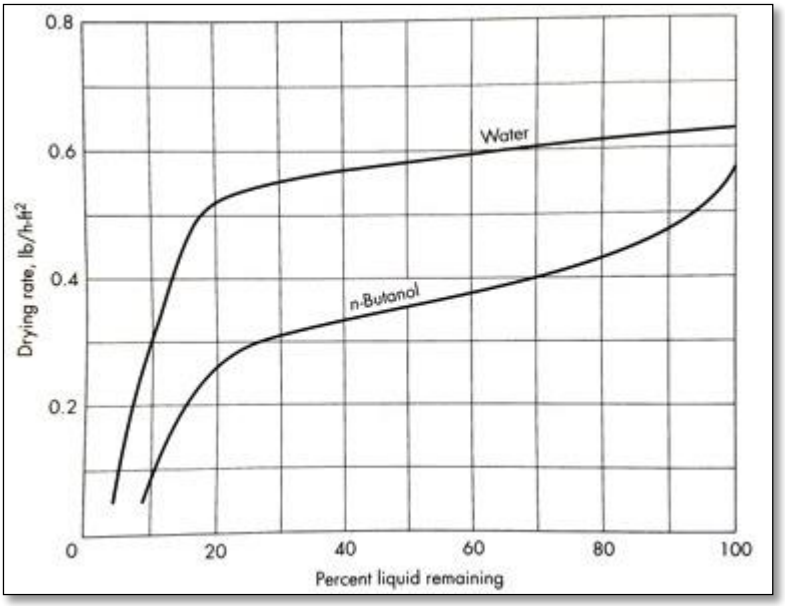
In the falling-rate period the relationship between drying rate and moisture concentration must be known. By assuming linear relation R=aX drying time of falling-rate period and total drying time can be calculated by Eq. 2.15 and 2.16.

at critical point: $a = \frac{R_{critical}}{X_{critical}}$

$$t_{falling-rate\ period} = (t_{total} - t_{constant-rate}) = \frac{m_s.X_{critical}}{A.R_{critical}} \ln\ (\frac{X_{critical}}{X_2'}) \qquad (2.15)$$

$$t_{total-drying} = t_{constant} + t_{falling} = \frac{m_s}{A.R_{critical}}\ (X_1 - X_{critical} + X_{critical}.\ln\frac{X_{critical}}{X_2'}) \qquad (2.16)$$

(a)



(b)

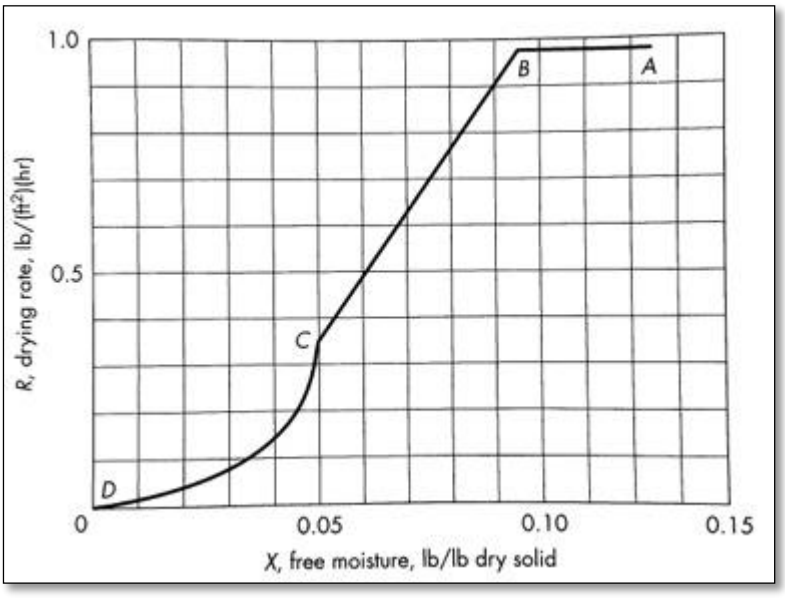


Figure 2.4. Drying rate curves of (a) beds of glass beads and (b) porous ceramic plate (Warren L. McCabe, 2005)

2.2. Sustainability and integrated bio-refinery

Sustainability of an industry, a technology, or a business comprises three aspects:

- Environmental aspects: if raw materials are supplied from renewable sources and if the practices to collect, aggregate, move and treat them doesn't damage the environment, quality of water, quality of air and wildlife diversity; and if the waste stream after products' lifetime would be biodegradable, then environmental aspect is met.

- Economic aspects**:** if the industry or company keeps acceptable profitability without subsidy of government, economic aspect is met.

- Social aspects**:** if the production and the use of final products don't harm the health, social justice and well being of the societies that use them, the third aspect is also met.

The integrated bio-refineries are currently known as the best route for production of bio-based fuels and chemicals. Such products have been identified to be more sustainable than fossil fuel products. Integrated bio-refinery facilities are analogously similar to petroleum refineries that use biomass conversion processes and equipment to produce a wide range of renewable products such as fuels, power, heat, steam and chemicals, from biomass. Due to the differences in biomass components, such plants can maximize the value derived from biomass feedstock by producing multiple products. Bio-refineries can produce a wide range of renewable fuels, green energy, green electricity and high value-added chemicals, by employing appropriate technologies. They are carbon neutral and have a vast environmental improvement over the fossil fuel technologies. Agriculture residues, municipal solid wastes (MSW), refused derived fuels (RDF), woody biomass, lignite, paper mill residue, black liquor and sludge can be used as feedstock in the bio-refinery.

2.2.1. Integration of gasification-based biorefinery to existing pulp and paper mill

TRI (ThermoChem Recovery Incorporation) gasification technology is, at the moment, the only technology that can gasify both solid and liquid (black liquor) biomass in a single gasification platform. It benefits the bio-refinery by gasifying a wide range of biomass types from small to large capacities (200 to 2000 odt/day) in one single steam reforming reaction vessel. By investing

on such technology, optionality is given in downstream by providing vast investment options (Figure 2.5).

Further to the sustainability advantage, the technology lowers the investment risks by enabling the bio-refinery plant to change the product portfolio quickly and cost effectively, in order to respond to the market changes. It is also flexible in accepting a wide range of biomass feedstock; therefore, the bio-refinery facility has the chance to react quickly to any feedstock market conditions. In addition, it has optimum thermal and process integration to produce combined heat and power, liquid fuels and bio-chemical products in the plant. Possible scenarios of using TRI technology are generally categorized as:

- Biomass conversion to syngas for liquid fuel and high value chemicals production
- Biomass conversion to syngas for combined cycle power generation to displace fossil fuel, decrease operating costs and increase revenue through selling excess green electricity to grid
- Biomass conversion to syngas for boiler and lime kiln applications for fossil fuel displacement and operating cost reduction

Due to the proprietary and unique features of the TRI technology, syngas specifications are entirely customizable to any production goal and scenarios, in order to maximize the economic and environmental benefits.

2.3. Biomass

2.3.1. Characteristics of woody biomass

Woody biomass is a loose particulate material that is derived from different sources that's why properties, sizes and moisture contents vary from one to another. It is mainly derived from forest harvesting, wood processing at mills, etc. Branches, roots and small tops are the biomass that come from the forest harvesting that are usually chopped into chips 30-50mm in length. In the sawmills, sawdust and cutoffs are generated from timber sawing and bark is generated from debarking step. Basic characteristics of different types of wet woody biomass are found in Table 2.1.

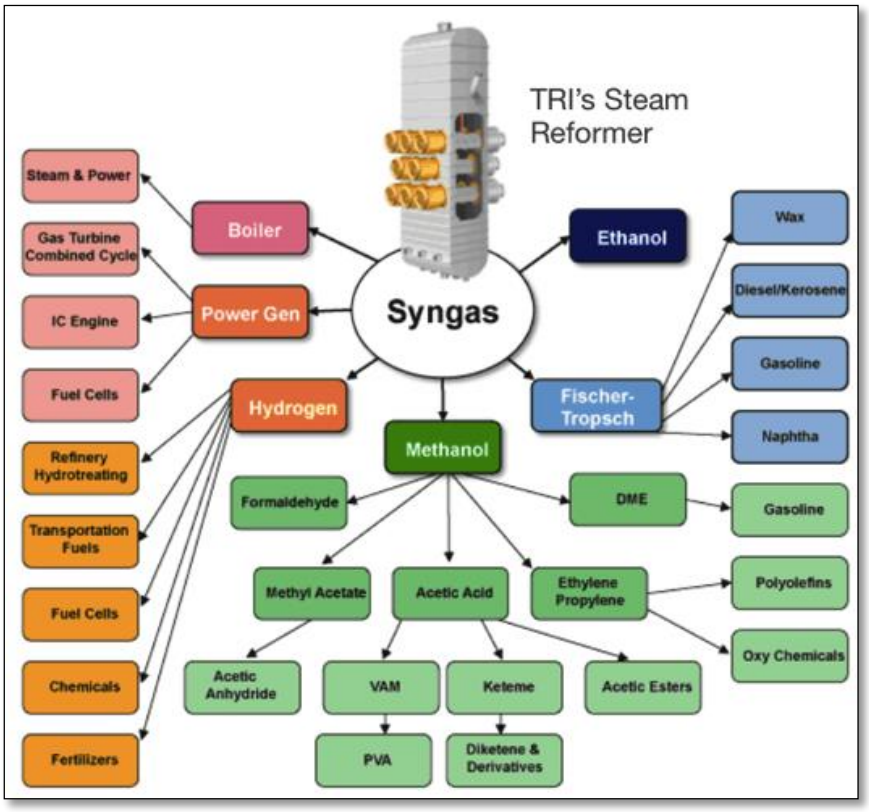


Figure 2.5. Downstream opportunities by investing on TRI gasification technology

Table 2.1. Basic characteristics of some woody biomass (Pang)

	Forest residue	Bark	Sawdust	Cutoffs
Size (mm)	Chips < 50	< 500	≤ 3	Chips < 50
Moisture content	50-100%	50-100%	50-100%	50-100%
Bulk density (kg/m^3)- dry base	250-300	250	100-120	250-300
Ash content	3-20%	3-20%	0.5-2%	0.5-5%

2.3.2. Moisture Content of biomass

Total quantity of water in the biomass including both bound and unbound moisture (see section 2.4.1). Total water is determined by either TGA (Thermo Gravimetric Analysis) or oven heating methods. In TGA, very small biomass samples (milligrams scale) is heated up steadily to about 110 °C and weighed simultaneously by a microbalance that is installed on the device, initial and final weights are then reported on a graph. In the oven heating method fresh samples are oven-

dried at about 105°C for 24 hours and it is weighed before and after heating. In both methods, the difference between initial and final mass is moisture content, which is divided by the initial mass to return a value in percent of moisture level (Eq. 2.17). In some works dry solid content is used instead of moisture content (Eq. 2.18).

$$Biomass\ Moisture\ Content\ (\%) = \frac{Initial\ Mass - Final\ Mass}{Initial\ Mass} \times 100 \qquad (2.17)$$

$$Biomass\ solid\ (\%) = 100 - biomass\ moisture\ (\%) \qquad (2.18)$$

2.3.3. Energy content and bulk density of biomass

Higher Heating Value (HHV) and Lower Heating Value (LHV) are the important parameters of biomass. In publications, they are typically reported in units of energy per dry unit of mass (kJ/kg dry or kcal/lb. dry). HHV represents maximum available energy that can be obtained from a given material. It is defined as total energy available from biomass combustion with air including the energy recovered from latent heat of steam that is produced during combustion. But LHV does not include such latent heat and it is defined as usable energy in the biomass. Increasing moisture content of biomass reduces usable energy content due to the presence of excess water in the matrix.

For quantifying the heating value (energy content) either empirical formulations or calorimetric bomb (that is more precise) is used. For empirical formulations, elemental analysis of biomass should be known. Equation 2.19 is a common formula called "Dulong formula" that estimates HHV of biomass by using percentage of C, H and S content from ultimate analysis (Kenneth Michael Frei, 2004):

$$Heat\ Content\ \left(\frac{Btu}{lb}\right) = 14495\ \times\ C + 61000\left(H - \frac{O}{8}\right) + 5770\ \times\ S \qquad (2.19)$$

Bulk density is important for: biomass transportation and reactor design. In contrary to liquids and other solid materials, bulk density of biomass is more complicated to predict. Moisture content, particle size and compaction are the parameters that influence the bulk density of

biomass. The higher the moisture content the higher the bulk density due to the void spaces filled with water. Therefore, different biomass types result different bulk densities.

2.4. Continuous Biodrying Technology (Navaee-Ardeh, 2009)

2.4.1. Different types of water in biomass

Unbound water and bound water are different types of water exists in the biomass. Unbound water consists of free water, interstitial water and a part of the surface water physically adhered to the surface of particles, whereas bound water is the one that is chemically embedded into the particles' structure. Each type requires different treatment mechanism for removal. During the drying process, as shown in Figure 2.6 qualitatively, free water is primarily removed at constant drying rate. Interstitial and surface water removals are then taking place during decreasing rate periods.

Constant rate drying takes place at wet-bulb temperature where convection is the dominant mechanism and external mass transfer controls the drying. Such drying depends on the air temperature, air relative humidity and air velocity Constant rate period is followed by first, second and third falling rate periods where more intense mechanism is required to pull the moisture to the surface of the particle. In such period, since the internal diffusion is the limiting factor, drying takes place at dry-bulb temperature. However, an efficient dewatering process can mechanically remove only a portion of free and interstitial water but surface and bound water requires thermal treatment technics.

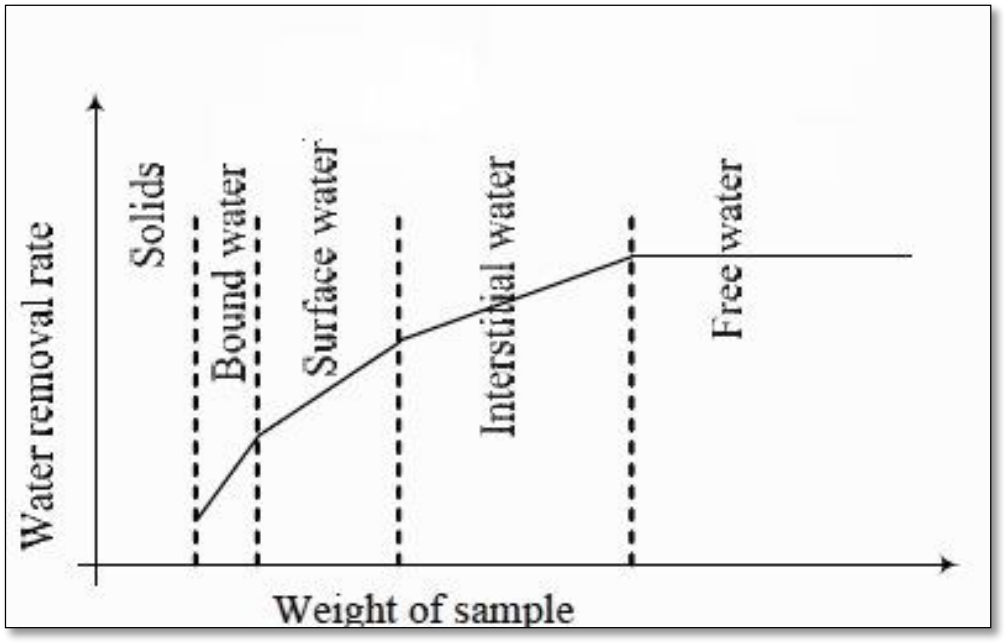


Figure 2.6. Typical drying curves of biomass [adapted from (Navaee-Ardeh, 2009)]

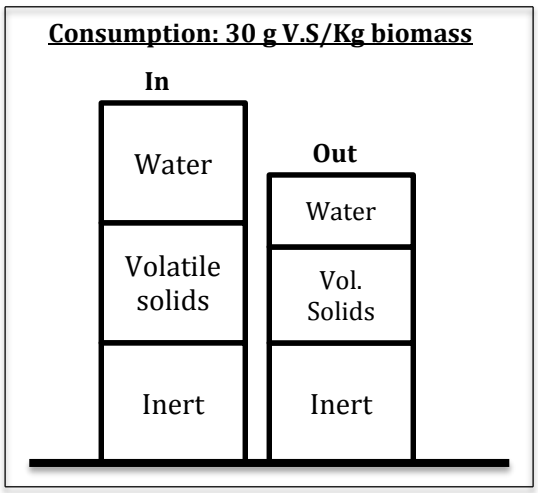


Figure 2.7. Biomass behavior before and after biodrying treatment [adapted from (Tambone et al., 2011)]

2.4.2. Continuous biodrying process

In the continuous biodrying process, in addition to forced convection the drying rate is enhanced by biological heat generated by metabolic activity of mesophilic and thermophilic microorganisms in the biomass matrix. Thus, biodrying is a self-heating process where heat generation mainly relies on the microbial activity in the biodrying reactor. Combination of forced convection and biological heat generation are employed in the technology to dry biomass. Principal transport mechanisms of moisture flow through the matrix are air convection and molecular diffusion. Air convection that is blown by engineered airflow is responsible for water losses that are easily removable. Biomass drying in the biodrying process happens in two steps:

- Water molecules are evaporated from the surface of biomass to surrounding air
- Evaporated water is conveyed out through the matrix and removed by convective airflow

Thermodynamic equilibrium between solid phase and air (gas phase) governs removal of water by convection. In the biodrying reactor physical and biochemical reactions happen to dry the materials. On the physical side there is convective moisture removal by controlled forced aeration and on the biochemical side aerobic biodegradation of readily decomposable organic matter occurs. In the latter, microorganisms catabolize biomass substrates during multiple biodegradation cycles to satisfy their metabolic and growth needs and ultimately lowers water content and volatile matters of biomass (Figure 2.7). General configuration of biodrying reactor and physio-biochemical phenomena that happens inside are similar to composting but the operating manner is different. Fast biodrying causes low biological stability and vice versa.

2.4.3. Microbiology of the biodrying technology

In biodrying reactor heat is generated by exothermic decomposition of the organic fraction of biomass. Biodrying technology is referred to the method of achieving mesophilic and thermophilic aerobic biological activity in the biodrying reactor. Aerobic decomposition of biomass is an exothermic process and biodrying reactor heats up as soon as bacteria decompose the organic matters. As temperature rises the biodegradation is accelerated resulting microbial growth rate increase, new cells production, rapid microbial multiplications and more CO_2 and H_2O generation. However, in the optimum temperature, microbial growth is at peak value, and further rise in temperature suppresses the microbial growth cycle, as microorganisms face with

thermal death. Several studies have reported the optimum range of microbial growth of thermophilic microorganisms in the range of 50-65°C. Important parameters in aerobic degradation process are: microbiology, oxygen, nutrient, and moisture requirements.

2.4.3.1. Microbial reaction in the biodrying reactor

Biodryer is a self-heating reactor that relies on the microbial heat generation to reach the drying temperatures. This is an advantage over conventional drying systems, which require an external heating source. Equation 2.20 shows the microbial reaction takes place in the biomass matrix in the biodryer.

$$Substrate + a\ O_2 \rightarrow b\ CO_2 + cH_2O + New\ cell \qquad \Delta H_r < 0 \qquad (2.20)$$

All types of woody biomass have common structure but they differ in chemical compositions. They are made up of cellulose fibrils bundled together and surrounded by hemicellulose and both are protected by lignin against biological and chemical attacks. Cellulose provides strength and flexibility to the wood, lignin cements the fibers together and hemicellulose helps these two bind together. These substrates represent readily decomposable part of biomass and have different degradability levels, which depends on the previous processing.

High degradability has been observed in the paper products that have chemically been processed to remove the lignin such as Kraft or sulfite delignification processes. Mechanical pulping does not remove the lignin but only destroy their structure, that's why the degradability of cellulose obtained from such process is lower (Haug, 1993). However, the most decomposable components are cellulose and hemicellulose and the least degradable is lignin.

Table 2.2. Degradability of biomass components (Haug, 1993)

Components	Degradability
Cellulose (from Kraft process)	90%
Cellulose (from mechanical pulping)	50%
Hemicellulose	70%
Lignin	0%
Lipids	50%
Protein	50%
Other sugars	70%

2.4.3.2 Classification of microorganisms in the biodrying process

Wide ranges of microorganisms (bacteria, fungi, etc.) catabolize organic compounds of the biomass. Psycrophiles are organisms that grow the best at 12-18 °C and sometimes at lower in the range of 5-10 °C. Ingraham et. al. reported very slow mesophilic generation at 8 °C where the best temperature was 25-40 °C; no mesophilic generation had been observed below 8 °C (Ingraham, 1958). The effectiveness of bacteria and fungi in decomposing the organic matters depends on the operational conditions of the process where they grow. Generally, different groups of organisms that perform biological activity are categorized into four groups based on their temperature tolerance (Navaee-Ardeh, 2009).

- Psychrophiles: active in temperature range of 0-20 °C
- Mesophiles: active in temperature range of 8-48 °C
- Thermophiles: active in temperature range of 42-68 °C
- Hyper thermophiles: active in temperature range of 70-110 °C

In continuous and batch biodrying reactors, typical temperature range of microbial degradation was reported as 15-50 °C where 65 °C was the highest observed temperature (Kenneth Michael Frei, 2004; Navaee-Ardeh, 2009; Roy, 2005). Such temperature range shows that bacteria involved in the process are mesophilic and thermophilic. The bacteria are very sensitive to the temperature of the matrix where they grow. As depicted in Figure 2.8 higher temperatures kill mesophilic bacteria while favoring the growth of thermophiles. Nevertheless, very high temperature causes death of thermophilic bacteria, as well.

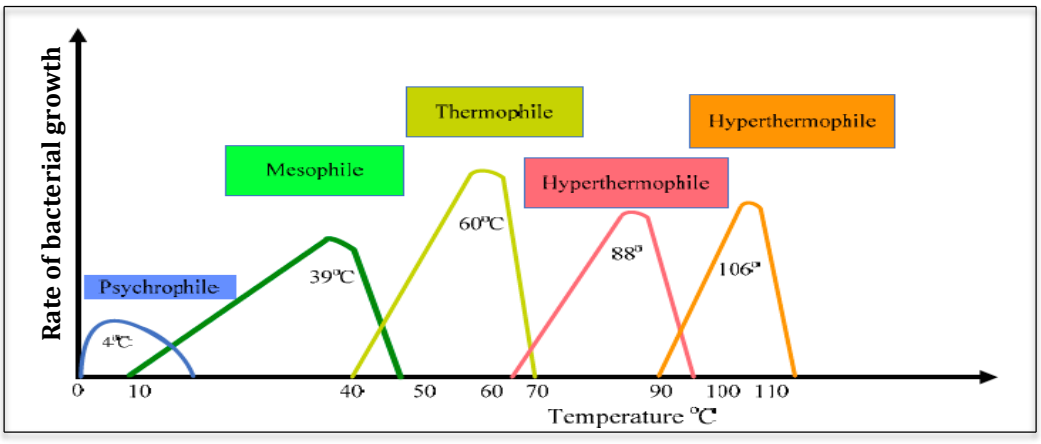


Figure 2.8. Temperature effect on microbial growth (Navaee-Ardeh, 2009)

2.4.3.3. Oxygen requirements and transfer mechanism

Availability of the oxygen is one of the important factors in biodegradation processes. Presence or absence of oxygen classifies the bioprocesses into aerobic and anaerobic. Aerobic biodegradation requires uniform and sufficient oxygen transfer to ensure optimum respiration of microorganisms for metabolic activity. In aerated composting, a compost pile requires 5-15% v/v oxygen or 21% v/v air (Navaee-Ardeh, 2009) which is equal to approximately 1-4 grams of oxygen per gram of biodegradable material (or approx. 4-17 gram of air per each gram of biomass material). This oxygen is only required for metabolism of microorganisms; thus, if drying of the material is supposed to be considered [like biodrying of this thesis], excess aeration rate at about 10-30 times than for biological oxidation is required. Air must properly be diffused and be able to reach all pores of biomass material to minimize anaerobic zones. If air does not penetrate into clumps of material, anaerobic conditions will be formed and developed. Anaerobic and aerobic decompositions are the different forms of biological activity that result different products (see section 2.5.5.5). Klass et. al. reported 30-60 °C for grass anaerobic decomposition in their experimental tests (Haug, 1993) and aerobic activity has been reported in the range of 35-65 °C (Kenneth Michael Frei, 2004; Navaee-Ardeh, 2009), which shows both can happen in similar temperature range. However, they both depends many factors that will be discussed in the upcoming sections.

Oxygen transfer to microorganisms is a very slow phenomenon that is controlled by diffusion mechanism. As shown in Figure 2.9, air is primarily supplied to the porous space of biomass and oxygen is then transferred to its gas/liquid interface, diffuses across the interface and finally reaches the microorganisms through the liquid phase where the microbial reaction (Equation 2.20) takes place. Microbial degradation then causes concentration gradient of oxygen and causes the diffusion of more O_2 from the air to the liquid phase. CO_2 and H_2O that are the products of the biological reaction are conversely moved towards the gas phase (air). Therefore, forced aeration in the biodrying process can enhance the mass transfer of oxygen.

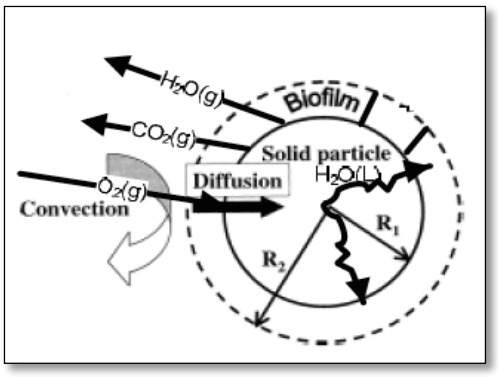


Figure 2.9. Oxygen transfer mechanism to microorganisms [adapted from (Navaee-Ardeh, 2009)]

2.4.3.4. Nutrients for microorganisms

Nitrogen (N), phosphorus (P), sulfur (S) and some other trace elements are key nutrients required by microorganisms and enough concentrations of them are necessary for proper cell growth. Ratio of carbon to nitrogen ofte represents nutrient parameter in the biomass. The ideal range of C/N for active microbial biodegradation is 20:1-30:1 (Navaee-Ardeh, 2009). Each biomass substrate has unique carbon to nitrogen ratio. Secondary sludge of pulp and paper mills has low C/N ratio whereas biomass like bark and fibers contain little nitrogen and consequently high C/N ratios. Table 2.3 shows carbon to nitrogen ratio of several biomass types.

Table 2.3. C/N ratio of different types of biomass [adapted from (Navaee-Ardeh, 2009)]

Biomass types	C/N ratio
Bark	160-534 : 1
Wood chips	492-535 : 1
Primary sludge	23-930 : 1
Secondary sludge	9-81 : 1
Mixed sludge	6-115 : 1

Negative linear correlation between C/N ratio of paper mill sludge and heat generation has been reported by Navaee-Ardeh et. al., 2009 (found by Larsen and McCartney, 2000), where high levels of heat generation occurring in the range of C/N=15-30. As the amount of bulking agent

(like bark) increases, the C/N ratio increases as well. The range of 24-29 has been recommended as the most ideal range for proper activity of microorganisms.

2.4.3.5. Moisture requirements of microorganisms

The minimum moisture content below which little or no microbial activity occurs has not been reported in the literature but from composting process 20% w/w can be considered (Velis et al., 2009). Moisture in the biomass is necessary and important for proper functioning of the microorganisms. High solid levels in biomass limits the transport of nutrient required by microorganisms to perform aerobic activity. On the other hand, high moisture level limits the availability of oxygen, which is due to the slow diffusion of oxygen into the thick water biofilm. Optimum moisture level required for acceptable microbial activity is in the range of 45-65% w/w.

2.4.4. Key variables of the continuous biodrying process

Relative humidity and temperature of the inlet air, airflow rate, relative humidity of outlet air, residence time, nutrient level (C/N ratio) and solid recycle ratio are important process variables in biodrying. Airflow rate and inlet air relative humidity directly affect the ability of system to eliminate moisture from biomass, air temperature affects the capacity of air to hold water for moisture removal, recycle ratio affects the acclimation period of microorganisms and residence time affects the capital cost of the system. Results of the previous biodrying studies at École polytechnique de Montréal where mixed sludge was dried show that the outlet relative humidity profile is the key variable in the continuous biodryer. Effect of different outlet relative humidity profiles on the efficiency index of biodryer was investigated and results reveals that the highest biodrying efficiency index is achieved if outlet air relative humidity profile is controlled at 85% in the first and second compartments and 96% in the third and fourth compartments of the reactor (see section 3.4.1). Such profile guarantees economic dry solid level of mixed sludge for boiler application.

2.4.5. Review and critical analysis of mixed sludge biodrying

In the continuous biodrying process, combination of forced convection and biological heat of microbial activity dries the biomass. These microorganisms are naturally present in the porous matrix of biomass. Attraction of biodrying compared to conventional drying technologies is that the reactor is self-heating and doesn’t need fossil fuel or external heating source. Biodrying

reactor has four nominal compartments and biomass is dried while moving downward in the reactor.

In the previous study, several parameters such as biomass type, biomass pH, biomass nutrient level (C/N ratio), residence time, recycle ratio, and outlet relative humidity profile were investigated and the key variables were determined by variable analysis. It has been reported that types of biomass and outlet relative humidity profile are the most influential parameters. Type of biomass corresponds to the nutrient level (C/N ratio) required by bacteria for performing biological activity and the outlet relative humidity corresponds to the quantity of water removed from the system. Generally, biomass is a mill specific parameter and in each single study it is considered as fix parameter, therefore, outlet relative humidity profile is the most influential parameter on the overall performance of continuous biodrying process.

Two levels for outlet relative humidity were investigated in the study: low RH level and high RH level. Low RH level had been set to 85%, which controls the drying at wet bulb temperature. Here, the drying takes place at constant rate and it is suitable for removing free and interstitial water of biomass. On the other hand, high RH level had been set to 96%, which controls the drying at dry bulb temperature. Such level helps activating the microorganisms and it is appropriate for falling-rate-period (see sections 2.1.2.6 & 2.4.1). It is suitable for removing the surface and bound water. Experimental tests resulted the best biodrying efficiency at outlet relative humidity profile that controls the removal of unbound water at wet-bulb temperature in the 1^{st} and 2^{nd} compartments of the reactor, and the removal of bound and surface water at dry-bulb temperature in the 3^{rd} and 4^{th} compartments.

Experiments and modeling data revealed that 25%-35% of the total drying in the biodrying reactor takes place in the first and second compartment where convection is dominant mechanism, and 65%-75% takes place in the third and fourth compartment where biological heat is generated and diffusion is the dominant mechanism. The previous experiments were conducted in 4-8 days residence time and wood waste was combined with the mixed sludge as bulking agent to help oxygen passes easily through the particles and reaches all the pores of biomass.

2.5. Pulp and paper sludge and disposal options (Kenneth Michael Frei, 2004)

2.5.1. Sludge generation

Pulp and paper mills are large consumers of water that is used at major process units such as woodchips washing, pulp washing, pulp slurry dilution, cooling systems, steam generation and etc. After being used, the water is ultimately discharged to the environment as effluent. Environmental regulations have obliged the industry to treat their effluents in wastewater facilities before sending them off to environment, in order to minimize the impacts on ecosystem, ("Water use and treatment in the Pulp and Paper industry," 2012). Pulp and paper mills generate in average 60 m^3 of wastewater per ton of produced paper (Kenneth Michael Frei, 2004) and the treatments generate primary and biological (secondary) sludge that remain problematic for the mills, which must be disposed according to environmental standards.

2.5.2. Sludge characteristics

Pulp and paper sludge is the biomass residue of mill's effluent, generated at primary and secondary (biological) treatment units. Primary sludge biomass is generated by gravity settlement at primary clarifier, which is mainly composed of fibrous materials (cellulose and hemicellulose) wasted from fiber recovery system of the pulp and paper process (Mahmood & Elliott, 2006). It is relatively easy to dewater. Secondary sludge biomass or waste activated sludge (WAS) is the residue of biological treatment unit where microorganisms consume organic compounds of the effluent (BOD) as food and eliminate about 90% of the BOD, the secure and harmless level for environment. The microorganisms are then extracted from secondary clarifier as solid waste after their normal life cycle. Quantity of secondary sludge depends on design and operation of the AST (Activated Sludge Treatment) system but roughly 40-85 kg of WAS biomass is generated per each ton of BOD removed from mill's effluent.

In secondary sludge biomass, considerable portion of molecular and cellular bound water (Navaee-Ardeh, 2009) makes it much more difficult than primary sludge for dewatering, therefore mills usually blend primary and secondary sludge to generate mixed sludge before mechanical dewatering (Mahmood & Elliott, 2006). Dewatering of mixed sludge with higher portion of the secondary sludge biomass is more complicated, which results lower dryness level after mechanical dewatering.

Different pulp and paper processes result different sludge characteristics. Table 2.4 shows some important characteristics of mixed sludge after mechanical dewatering have been shown.

Table 2.4. Characteristics of mixed sludge after mechanical dewatering
[adapted from (Kenneth Michael Frei, 2004)]

Parameters	Pulp mill	De-inking mill	Recycled paper mill
Moisture content	64%	58%	52%
Elemental analysis:			
Carbon	50.6%	30%	48.5%
Hydrogen	6.2%	3.9%	6.6%
Oxygen	32.2%	24.5%	41.5%
Nitrogen	3.1%	0.7%	0.5%
Sulfur	0.8%	0.2%	0.3%
Ash	6.5%	40.7%	2.9%
HHV- dry (KJ/kg)	21,725	12,112	20,700
Bulk density (Kg/m^3)	400-700	400-700	400-700

Note: Data related to average of several mills

2.5.3. Secondary (biological) wastewater treatment process

Pulp and paper mills are obliged to install biological (secondary) treatment system on their wastewater facilities, which the consequence is reduction of biological oxygen demand (BOD) discharged to environment. Unlike the primary treatment, purpose of the secondary unit is to remove organic substances from wastewater. The activated sludge process is one of the most common methods used for this purpose.

Wastewater, after being treated in the primary unit, is fed to an aerated basin where biological treatment takes place (Figure 2.10). Microorganisms degrade the waste and after normal life cycle they are extracted from secondary clarifier as a solid waste stream. A portion of this cellular mass is recycled to the inlet of secondary treatment to maintain the microbial population but a certain quantity is wasted in the form of waste activated sludge (WAS) or secondary sludge.

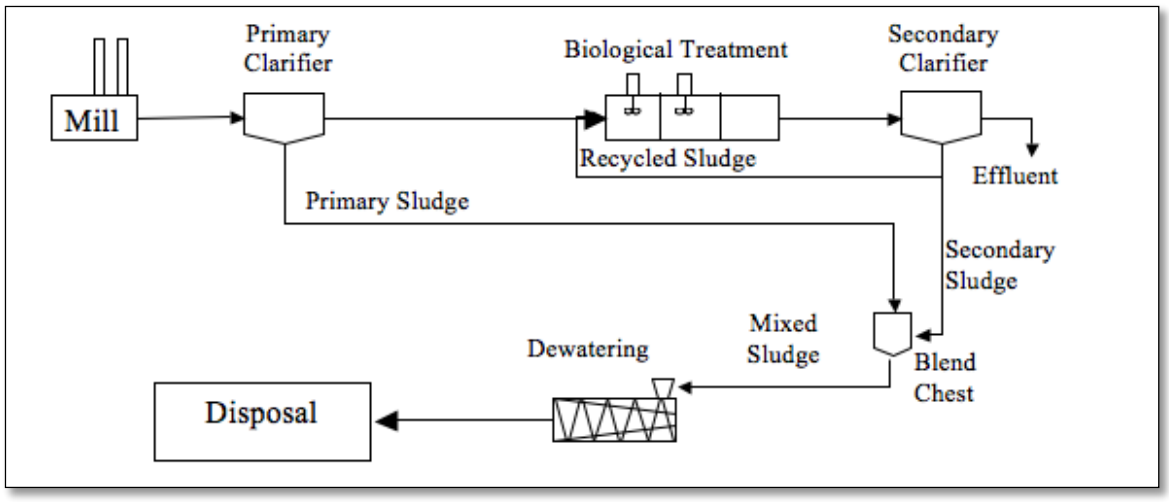


Figure 2.10. Schematic of wastewater treatment process [adapted from (Kenneth Michael Frei, 2004)]

2.5.4. Sludge dewatering before disposal

Ratio of biological to primary sludge is important for mechanical dewatering step. Typical ratio of mixed sludge is in the range of 0.4, containing 40% biological sludge (dry mass). Recently, the quantity of primary sludge has been decreased in wastewater streams mainly due to process optimizations in the pulp and paper mills (closing water systems and keeping valuable fiber in the process rather than sending them to sewer). On the other hand the dissolved organic concentrations are increasing. The consequent is rising of the biological to primary sludge ratio to over 0.5, which enormously increases the challenge of sludge dewatering by mechanical devices (mechanical dewatering process).

Sludge dewatering has three steps: sludge pre-conditioning, pre-thickening, and dewatering or thickening. In the pre-conditioning unit, primary and biological sludge are mixed in a blend tank and polymers (coagulants & flocculants agents) will be added to help coagulating and flocculating the solid particles. Then, sludge enters the pre-thickening unit that is often a gravity table or rotary sludge thickener (RST). They reduce moisture content of mixed sludge from 97-99% to about 90-92%. Sludge then enters dewatering unit where the moisture is mechanically reduced to about 60-85% depending on the type of technology used. The most common dewatering devices are belt and screw presses. Screw press usually shows better performance where dewaters the mixed sludge to about 60% moisture level whereas belt presses dewaters to about 75-80%. However, inefficient pre-conditioning, non-optimized dewatering operations, and

higher portion of secondary sludge makes screw presses achieve only 70% (and even higher) moisture level.

2.5.5. Disposal options in the pulp and paper mills

Disposal options are classified into non-beneficial and beneficial disposals. Non-beneficial include: landfilling, incineration (other than steam production) and ocean dumping. Beneficial options are: aerobic composting, anaerobic composting, and thermal treatment for energy recovery. There are also several other beneficial options such as agricultural applications, landfill cover and animal bed lining and etc. The most practiced disposal methods in pulp and paper industry are landfilling, combustion (steam production in power boiler), composting and land-spreading.

2.5.5.1. Landfilling

Landfilling is the most common non-beneficial disposal practice becomes less favorable due to shortage of landfill spaces, public opposition for opening new landfills, and more importantly high costs (Kenneth Michael Frei, 2004; Mahmood & Elliott, 2006). Landfilling must be practiced according to the environmental regulations, which raises the costs. Therefore, mills prefer to stay away from landfilling and look for beneficial options.

2.5.5.2. Incineration

Incineration is an option to simply reduce the volume of the sludge in order to economy the disposal costs. The main purpose of incineration is to destroy the pathogens and contaminations before landfilling. The energy of biomass is not recovered in such method. Incineration technic is widely practiced by municipalities for disposing municipal wastes where there are a lot of contaminations.

2.5.5.3. Land-spreading

Land-spreading is among the beneficial technics that enriches the quality of soils for agriculture purposes. In such method, sludge is spread over the agricultural lands where carbon and other nutrients (N, P) improve the soil quality and prepare it for agriculture purposes. Land-spreading is capital-intensive due to storage and spreading equipment requirements.

2.5.5.4. Aerobic composting (aerobic microbial degradation)

In composting, microorganisms decompose the organic matter of biomass very slowly and release carbon dioxide, water and heat. Such degradation produces organic materials that are used for soil amendment. This technique is an alternative to landfilling option but requires certain infrastructures and equipment, which results higher initial costs. A New Zealand based company has developed a continuous composting reactor for municipal waste (MSW) treatment application. The technology works under "plug flow" principles. Biomass moves downward in the reactor by means of the gravity force (Figure 2.11). Residence time is 14-21 days that is much shorter than convectional composting reactors (more than 30 days). Biological heat raises the reactor's temperature to 40-70°C appropriate level to destroy pathogens of MSW. Such system does not require external heating source and air injection and it has been claimed to be energy-efficient with minimal moving parts, maintenance and operating costs.

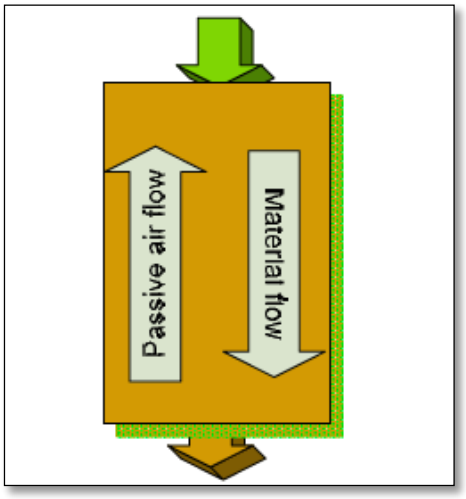


Figure 2.11. General overview of vertical composting reactor

(Navaee-Ardeh, 2009)

2.5.5.5. Anaerobic composting (anaerobic microbial digestion)

Composting in the absence of oxygen is called anaerobic digestion. Methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S) and water are the results of anaerobic digestion. Such option is costly and requires complex infrastructures such as gas tight reactor and gas capture system.

2.5.5.6. Thermal treatment options

Thermal processes are among the beneficial disposal options, which are available to recover the calorific value of biomass. Thermochemical processes such as gasification, combustion and pyrolysis are among the possible routes for energy recovery. Gasification is partial oxidation of biomass at high temperatures (limited air flow) results intermediate gas composed of mainly carbon monoxide, hydrogen and methane (see section 2.6) that can either be burnt or used for biofuel production. Pyrolysis is briefly described as heating up the biomass in complete absence of oxygen that results char, fuel gases and bio-oil. Combustion is complete oxidation of biomass mainly to recover biomass energy for steam generation.

Complex environmental regulations for land-spreading and composting as well as the rising energy costs oblige pulp and paper mills to dispose their sludge biomass in combustion boilers (Shahram Navaee-Ardeh, 2006). Sludge biomass, once dried, can be used as boiler fuel with HHV of 18-21 GJ/dry-ton (see section 2.5.2) comparable to some wood species (K.M. Frei, 2006). However, an efficient boiler application requires dewatering of sludge to dryness level more than 40% (Shahram Navaee-Ardeh, 2006).

2.5.5.7. Short discussion (1)

Since varieties of beneficial disposal options are available, it is crucial that each mill to assess individually the options economically, technologically and environmentally and determine the best option based on its own conditions and criteria. Profitable options are varied from process to process and differ from case to case; therefore techno-economic assessments will be helpful.

2.6. Gasification technologies

2.6.1. Introduction (A.V. Bridgwater, 2002; Kei Yamashita, 2004; McKendry, 2002; Newport et al., 2012)

Gasification is a thermochemical platform of biomass conversion, which converts almost all types of carbon-based biomass into a wide range of downstream value-added products. The process is used to ultimately synthesize hydrogen, fuels and various chemical compounds. It offers a significant potential to transform locally available feedstock (energy crops, agriculture and animal wastes, refuse derived fuel or RDF, etc.) into fuels, chemicals, electricity and process

heat. Technically, gasification is the conversion of biomass to a gaseous fuel by heating in a gasifying medium such as air, oxygen or steam. It is a high-temperature pathway for upgrading the relatively low-grade fuel (wood or other residues) to a clean gaseous fuel for either heat and power application or fuel/chemical synthesis.

In the gasification process, a portion of the energy of biomass feedstock is retained in the syngas mixture. Limited oxygen, air or steam or combination of them –depending on the technology- is served as gasifying agent. The product gas consists of carbon monoxide and hydrogen with certain amounts of carbon dioxide, water vapor, methane and trace amounts of ethylene, ethane and higher hydrocarbons, nitrogen (if air used as gasifying agent) and some contaminants such as small char particles, ash, tars, ammonia, acids and alkalis.

Typical energy content of syngas is 4–18 MJ/Nm^3 depending on the gasifying agent and the technology used. When air is used as gasifying agent (air-blown gasifiers), large fraction of the nitrogen of the air dilutes the syngas and reduces net calorific value (NCV) of the syngas to the range of 4-6 MJ/Nm^3, which makes it suitable for boiler application as well as engine and turbine use. When oxygen is used (oxygen-blown gasifier) the syngas doesn't contain nitrogen and is rich in hydrogen (H_2) and carbon monoxide (CO) with high calorific value in the range of 10-15 MJ/Nm^3, which is sufficient for limited pipeline transport and syngas conversion. However, an air separation unit (ASU) must be added that increases investment costs and makes it less attractive for small-scale facilities. Finally, Steam gasification leads to medium calorific value nitrogen-free syngas with low tar and high hydrogen contents.

Gasification has four stages: drying, de-volatilization (pyrolysis), combustion and reduction. Moisture is first evaporated due to heat in the drying zone, more heat beyond the dehydration temperature causes thermal decomposition where volatile matters of biomass are decomposed into volatile gases, intermediate vapor and the carbon structure known as 'char'. Then combustion occurs to provide required heat for endothermic reaction of reduction stage, which are the equations 2.21-2.29.

$Water - Gas\ reaction$: $C + H_2O \rightarrow H_2 + CO \quad \Delta H = +131\ MJ/Kmol$ (2.21)

$Water - Gas\ shift\ reaction$: $CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H = -41\ MJ/Kmol$ (2.22)

$Boudouard\ reaction$: $C + CO_2 \rightarrow 2CO \quad \Delta H = +172\ MJ/Kmol$ (2.23)

$Methanation$: $CO + 3H_2 \rightarrow CH_4 + H_2O$ (2.24)

$C + 2H_2 \rightarrow CH_4 \quad \Delta H = -75\ MJ/Kmol$ (2.25)

$Steam - methane\ reforming$: $CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta H = +206\ MJ/Kmol$ (2.26)

$Partial\ oxidation$: $C + \frac{1}{2}O_2 \rightarrow CO \quad \Delta H = -111\ MJ/Kmol$ (2.27)

$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad \Delta H = -283\ MJ/Kmol$ (2.28)

$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \Delta H = -242\ MJ/Kmol$ (2.29)

Heat supply through the combustion might be either partial meaning that a part of biomass is directly combusted in the gasifier (direct heating), or might be complete meaning that combustible gases are combusted in heat exchangers (indirect heating). Conventional technologies (fixed bed technologies) use the first whereas recent technologies (TRI technology) use the latter in order to increase the heat transfer efficiency to the gasifier's bed.

2.6.2. Classification of gasification technologies

Gasification technologies are classified into two main groups where each of them is divided to several types:

1) Conventional gasification technologies:
   a. Fixed bed technologies
      - Downdraft gasification technology
      - Updraft gasification technology
      - Cross-flow gasification technology
   b. Entrained flow technology

2) Fluidized bed (FB) technologies:
   - Circulating fluidized bed (CFB) gasification technology

- Dual fluidized bed (DFB) gasification technology
- Bubbling fluidized bed (BFB) gasification technology

2.6.3. Conventional gasification technologies

Fixed bed gasifiers or traditional gasification technologies are among the first developed technologies since the advent of biomass gasification. They are classified into downdraft, updraft and cross-draft depending on the direction of the airflow. Simple design and inexpensive cost are the advantages of conventional technologies. Since air is used as the gasifying agent, huge portion of produced gas contains N_2 that dilutes the syngas and reduces the energy content and results LCV (Low Calorific Value) syngas in the range of 4-6 MJ/Nm^3. Maintaining uniform radial temperature profile across the bed and channeling potential are among the challenges in such technologies.

2.6.4. Fluidized bed (FB) gasification technologies

In the fluidized beds, the gasifying agent creates turbulence through the bed and fluidizes inert bed materials. Gasifying agent can be air, oxygen, steam or a combination of air-steam or oxygen-steam. In FB reactors, biomass is mixed with hot inert materials that create high heat and mass transfer rates. Although they work at the same temperature range as fixed bed but it is superior since it brings uniform temperature distribution across the bed and high heat and mass transfer efficiencies. The technology is flexible in terms of biomass feedstock and has high carbon conversion efficiency (Loha, Chattopadhyay, & Chatterjee, 2011).

Fluidized bed gasifier is known to have advantage of treating the biomass with relatively high moisture content compared to other technologies and it is easy to scale up. Three types of fluidized bed have already been investigated:

- Circulating fluidized bed (CFB)
- Dual fluidized bed (DFB)
- Bubbling fluidized bed (BFB)

2.6.4.1. Circulating fluidized-bed (CFB) technology (Li et al., 2004; Ryan M. Swanson, 2010)

In CFB, the inert bed materials and produced char are circulated between reactor and cyclone separator (Figure 2.12). In the separator, the syngas leaves from the top, ash is removed from the stream, bed materials and char are recycled back to the reaction vessel through a cyclone for further utilization. Either turbulent or fast fluidization flow regimes are made through the bed. Heat transfer here is less efficient than bubbling fluidized bed (BFB) (see section 2.6.6.3) systems, and the range of particle sizes are also limited. The CFB gasifier is at the earlier stage of development than BFB gasifier.

2.6.4.2. Dual fluidized bed (DFB) technology (Murakami et al., 2007; G. Xu, Murakami, Suda, Matsuzaw, & Tani, 2009)

Here, combustion is isolated in a separated chamber to supply required heat of gasification. Gasification and pyrolysis stages occur in a dense bubbling turbulent fluidized bed by contacting the heat carrier particles (HCP) and interacting with the gasification agents (air, steam). Produced char in the pyrolysis stage and HCPs (inert bed materials) are conveyed to the adjacent chamber where char is combusted and heats up the HCPs, then returned back to the bed to supply heat of endothermic reactions (Figure 2.13).

Produced gases move upward, interacting with hot particles while passing through the freeboard, which results tar/hydrocarbon reforming as well as cracking and water gas shift (WGS). These gas-upgrading reactions do not considerably reduce the temperature of the HCPs so that the particles can consequently be employed in the gasifier for highly endothermic gasification and pyrolysis stages. By DFB gasifier middle calorific value syngas that has a vast range of applications can be obtained.

2.6.4.3. Bubbling fluidized bed (BFB) technology (Ian Narvaez, 1996; Ryan M. Swanson, 2010)

Such gasifiers use a bed of fine and inert particles with good thermal characteristics. Quartz sand, silica sand, olivine and Ni-alumina catalyst are among typical bed materials used in BFB. The technology is either directly heated by combustion reactions in the bed, or indirectly heated through the series of heat exchangers or external combustors (Figure 2.14). In bubbling beds, the gasifying agent is forced through the bed of inert particles and the velocity is set in a way that

"fluidization" occurs, but at the same time particles remain in the reactor. Such mechanism ensures good heat transfer in the reactor and effectively break up the biomass feed, which results high biomass conversion rate and low tar production.

BFB technology has already undergone extensive demonstration programs under a wide range of conditions and biomass feedstock. Main product (syngas) moves out from the top, and ash along with the produced char fall out from the bottom or sides.

Among the fluidized bed technologies, bubbling bed gasifiers are flexible to biomass feedstock (from wood pellets to rice husk) with various particle sizes, and has simpler concept, which provide high heat transfer rate between bed materials and biomass fuel and create uniform temperature distribution throughout the reactor. They are able to generate uniform syngas with low tar content and unconverted carbon. Although BFBs have been extensively applied for biomass gasification, the operating conditions and optimized parameters differ according to the desired output of project.

2.6.5. TRI gasification technology

TRI (ThermoChem Recovery International) gasification technology is the focus of this thesis and the study of implementation of biodrying system to a gasifier has been generally investigated on such technology. It is an advanced bubbling fluidized bed (BFB) biomass to syngas system for green energy solutions. It employs indirectly heated fluidized bed steam reforming process to convert any carbonaceous biomass feedstock into high quality syngas, from which higher value products is produced. The technology consists of two stages where steam reforming takes place at 1^{st} and gasification (partial oxidation) at the 2^{nd} stage:

a. Principal stage (1^{st} stage): medium temperature low-pressure fluidized bed steam reformer, where endothermic steam reforming reaction plays key role. Bed temperature is adjusted based on the feedstock properties but it is always below the slagging temperature of the biomass components. This stage has three inputs (biomass feed, superheat steam, combustion fuel & air) and three outputs (H_2-rich syngas, clean flue gas, bed drain such as ash and unreacted char), shown in (Figure 2.15). Steam reforming is a specific reaction where steam reacts with organic carbon to form carbon monoxide and hydrogen. Steam also reacts with the

produced CO to form more H_2. When biomass enters the reformer, remaining moisture of the biomass is evaporated, then volatile matters are released through pyrolysis and produced char undergoes steam reforming. Reactions 2.30-2.33 have been reported to take place in the steam-reforming unit.

$$C_{(s)} + H_2O \rightarrow CO + H_2 \quad (2.30)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2.31)$$

$$C_{(s)} + CO_2 \rightarrow 2CO \quad (2.32)$$

$$C_{(s)} + 2H_2 \rightarrow CH_4 \quad (2.33)$$

Biomass is fed from the side close to the bottom. Few cyclones have been designed inside the column on the top to capture flying ashes and chars and conveying them back to the fluidized bed through dipleg (Figure 2.16-a, Figure 2.16-b). The remaining chars and ashes in the syngas are captured at external cyclones designed at reformer's outlet.

Steam injection is made through a set of spargers designed at the bottom of the bed (Figure 2.16-c). Solid fraction of biomass is gradually turned to gas when it moves upward (Figure 2.17). When biomass enters the reformer fluidizing steam first dries it and then moves it upward where temperature rises. Higher temperature and lack of oxygen then causes pyrolysis where volatile matters are released and primary carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and char (C_s) are formed. They keep on moving upward to the highest temperature region where char is reacted with the steam to form more carbon monoxide and hydrogen. High temperature of this region facilitates water-gas-shift (Equation 2.31) and Boudouard (Equation 2.32) reactions, which cause more hydrogen production.

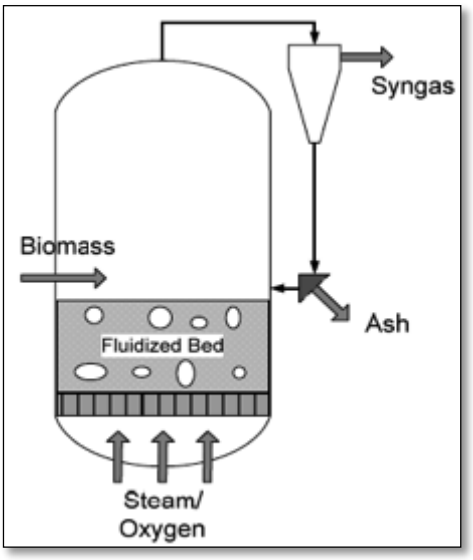


Figure 2.12. Schematic of circulating fluidized bed (CFB) gasification technology [adapted from (Ryan M. Swanson, 2010)]

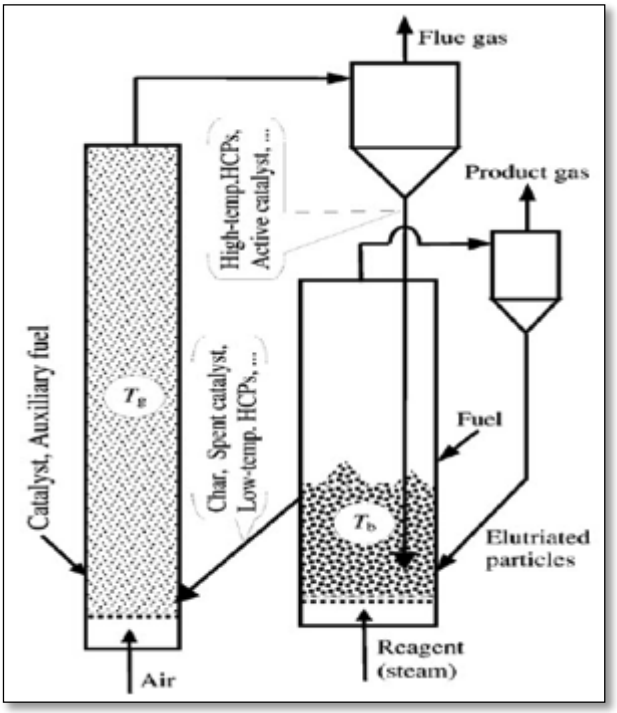


Figure 2.13. Schematic of dual fluidized bed (DFB) gasification technology [adapted from (G. Xu et al., 2009)]

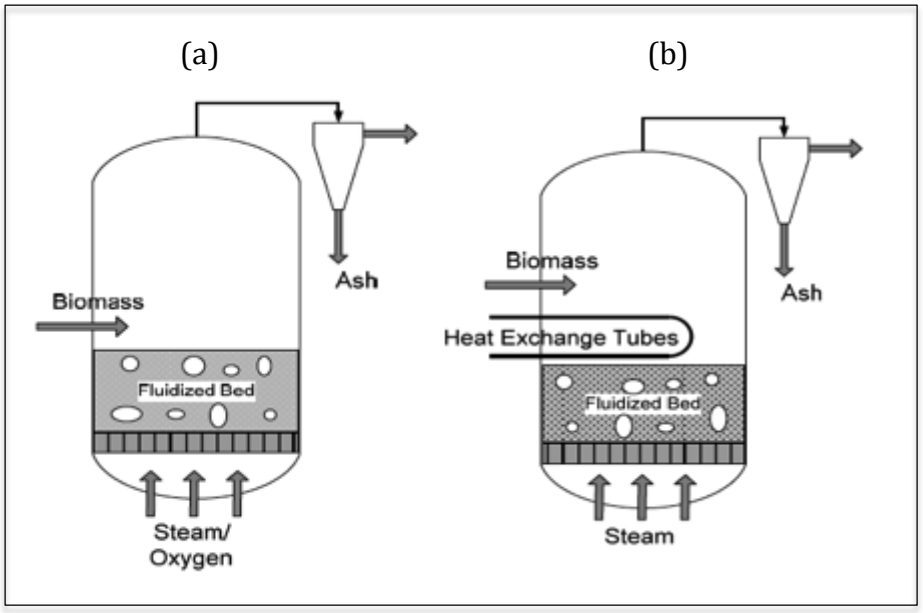


Figure 2.14. Bubbling fluidized bed (BFB) gasification technologies: (a) directly heated, (b) indirectly heated via heat exchange tubes (Ryan M. Swanson, 2010)

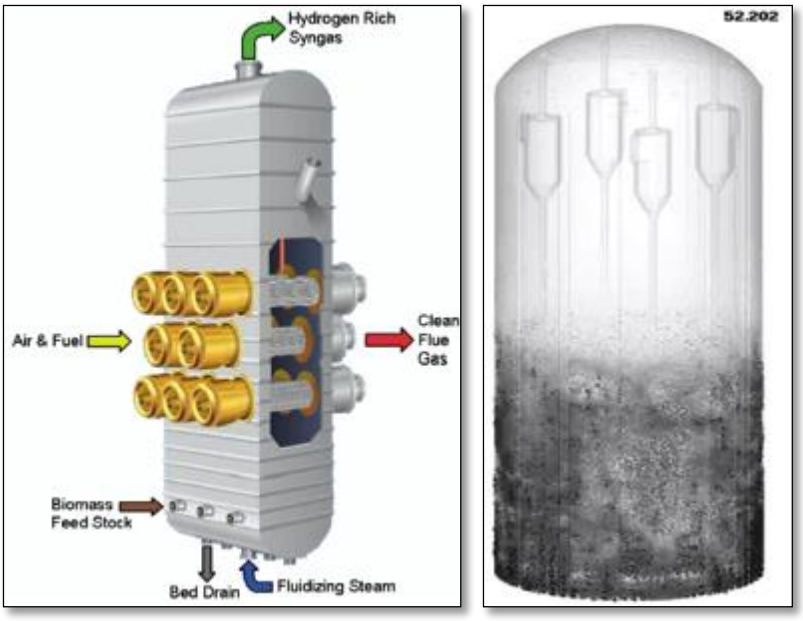


Figure 2.15. Overview of ThermoChem Recovery International (TRI) steam reformer

b. Complementary stage (2nd stage): higher temperature low-pressure fluidized bed gasification unit called carbon trim cell (CTC) where exothermic partial oxidation takes place inside. It's a refractory lined vessel fitted with fluidization grid, which is installed beside the steam reformer to gasify fine char leaving the reformer, through limiting the oxygen (partial oxidation). The principal role of the unit is to adjust H_2/CO ratio in order to meet the downstream requirement. A proprietary solids collection system is installed on the steam reformer's syngas discharge (1st stage) to collect ash/char elutriated from the reformer; they are then routed to the CTC and limited oxygen is utilized for converting the residual carbon to gas based on the reaction 2.34 (Newport et al., 2012).

$$2C_{(s)} + O_2 \rightarrow 2CO \qquad (2.34)$$

TRI gasification technology produces medium calorific value hydrogen-rich syngas that can be used in the biofuel production, biochemical production, steam generation, and power generation through fuel cells or combined heat and power cycle (CHPC). The technology accepts a wide range of biomass feedstock either liquid or solid. For liquid feedstock (like black liquor), sodium carbonate (Na_2CO_3) is used as bed material whereas for solid biomass feedstock (like forest/agriculture residue), sand or alumina oxide or other inert solid materials are employed. Heat of endothermic steam reforming reactions is supplied indirectly by pulse combustion heat exchangers (PC Heaters), shown in Figure 2.18. Tube bundles of the heaters are completely submerged in the bed materials and reformer's bed level fully covers the bundles. Since heat resistance inside and outside of the tube bundles is small, overall heat transfer of PC heaters is much higher than the conventional combusting systems. Inside the tube, heat resistance is inherently high but due to the altered flue gas direction, heat transfer coefficient is improved (boundary layer of tube's inside is continuously scrubbed away). Outside the tube heat transfer coefficient is also high due to the nature of the bed materials (Newport et al., 2012; "Project Independence Study: Liquid fuels from bimoass, feasibility study - Scope and estimates," 2010; "TRI Biomass gasification- How it works," 2015).

Pulse combustion mechanism provides high heat transfer efficiency. Germans had primarily developed such mechanism for their rockets' propulsion systems in World War II. The Mechanism consists of a two-stroke engine based on the Helmholtz Resonator principle without

any moving parts. As shown in Figure 2.19, fuel and air are introduced through a proprietary aero-valve and ignited with a pilot flame causes combustion and flue gas generation. Combustion causes expansion, which results hot gas to rush down the resonance tube and leave the chamber. This incident creates vacuum in the combustion chamber causes fresh fuel-air mixture to be sucked-in from one side, and a portion of the hot flue gas in reverse direction from the other side. Contact of the reverse hot flue gas and air-fuel mixture causes compression and creates subsequent ignition. This mechanism is repeated continuously with the frequency of 60 Hz (60 times per second). High combustion efficiency of the pulse combustion technic is due to the superior air-fuel mixing, excellent compression-ignition sequence and uniform heat flux distribution through the length of the tubes. Pulsations in the resonance tubes produce a gas-side heat transfer coefficient that is several times greater than a conventional fire-tube heater. This efficient heat transfer reduces the size and cost of the heat exchangers and steam reformer ("TRI Biomass gasification- How it works," 2015).

TRI gasification is insensitive to fluctuations of feed rate, moisture content and biomass calorific value because of unique attribute of pulse combustion technology, which cause stability to gasification process. By supplying the required heat of steam reforming, indirectly by PC heaters, produced syngas is not diluted by N_2 and process will result medium calorific value syngas. Fuel flexibility is also an advantage of the pulse combustion system, which is installed on TRI technology. It accepts any combustible gas including natural gas, syngas or waste tail gases of downstream processes. Several benefits makes this technology unique compared to other gasification technologies among them are:

- Feedstock flexibility makes the process accepting a wide range of carbonaceous materials such as forest residue, agriculture residue, black liquor, industrial wastes and sludge, construction demolition debris, animal wastes like poultry litter and cattle manure, MSW & RDF and etc.

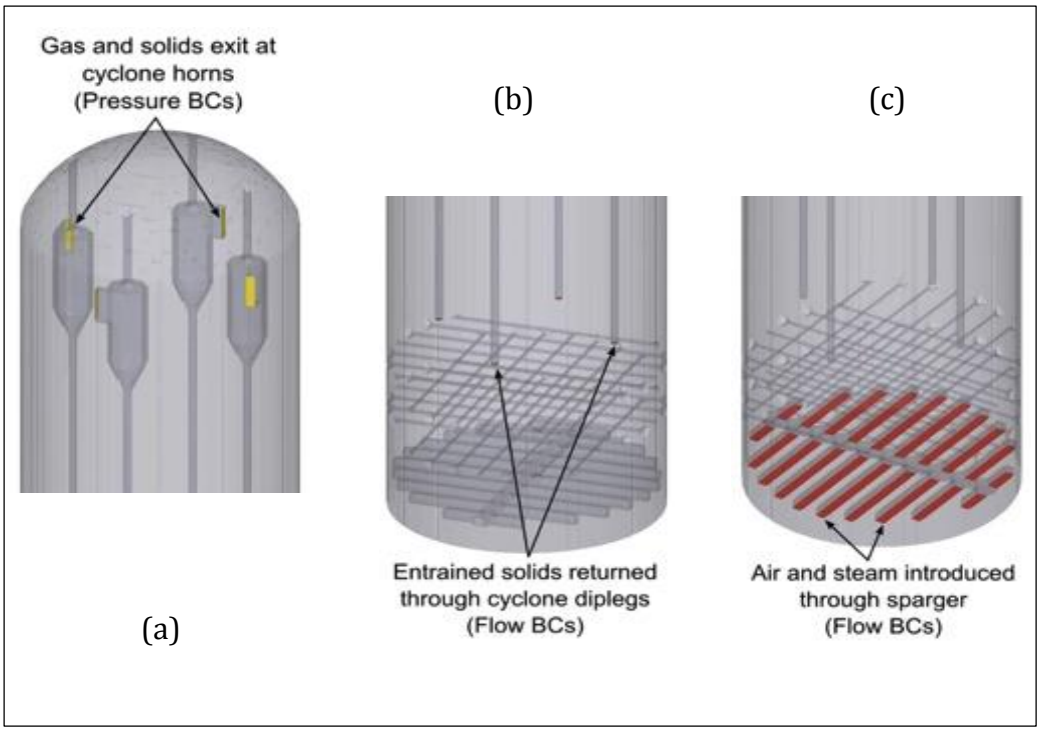


Figure 2.16. Top and bottom of TRI steam reformer: (a) interior cyclones (b) dip legs (c) spargers of steam distribution

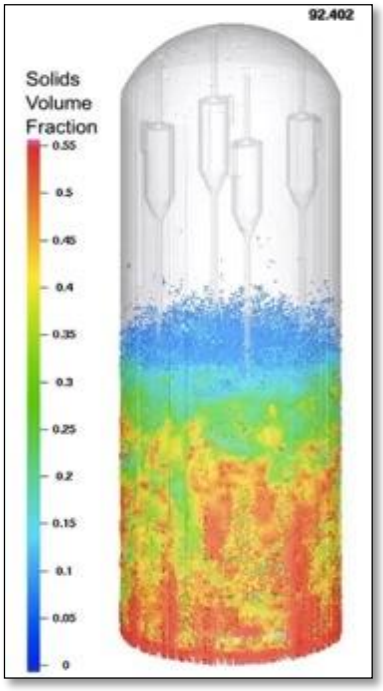


Figure 2.17. Solid fraction of biomass along the TRI steam reformer's height

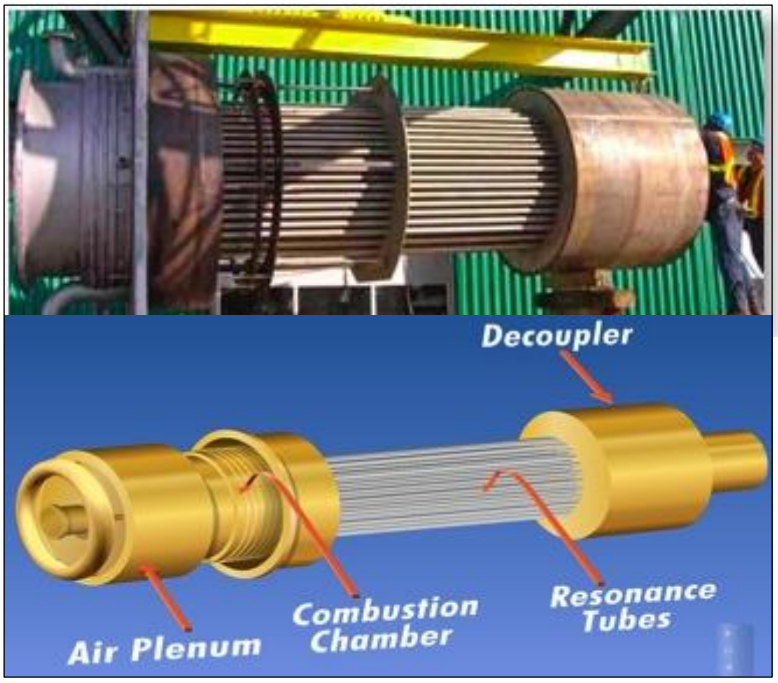


Figure 2.18. Pulse combustion heat exchangers (PC heater) of TRI steam reformer

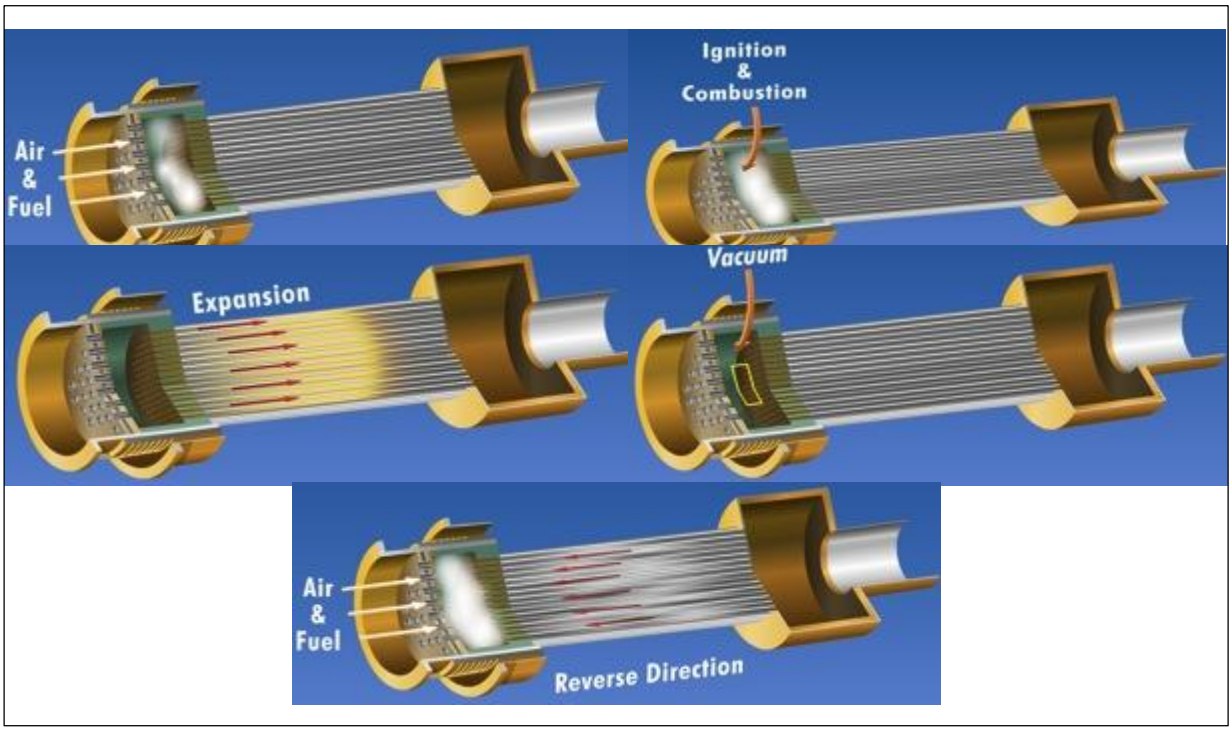


Figure 2.19. Mechanism of pulse combustion system

- Production of medium calorific value syngas independently from feedstock
- Adjustable H_2/CO ratio independently from biomass feed
- Non-slagging system
- Ultra-low emission system due to pulse combustion technology

TRI Corp. successfully constructed and commissioned a small process demonstration unit (PDU) at Durham, North Carolina that was processing 4 dry tons per day (1 MW_{th}) of biomass (Newport et al., 2012). Afterward, they successfully established and commissioned their commercial scale demonstration unit with partnership of NewPage Inc. who had severely suffered from downturn in economy. The process was integrated at Wisconsin Rapids Mill (a pulp and paper mill) in Wisconsin (North Carolina), to gasify 500 dry ton of biomass per day. Feedstock was forest products and the project was called "Project Independence" (Freeman, 2012).

2.6.8. Energy efficiencies of gasification process

Energy efficiency or first thermodynamic law efficiency is an indication of the gasifier's performance, the higher the efficiency the better the process. It is expressed in two different ways (Loha et al., 2011): hot gas efficiency, which is the ratio of product gas's energy including sensible energy, over the stored energy in biomass plus energy of input steam and external energy (Eq. 2.35); and Cold gas efficiency that excludes the sensible energy of the Eq. 2.35. It is defined as the ratio of syngas energy over energy of biomass plus energy of input steam and external energy (Eq. 2.36).

$$\eta_{hot\ gas} = \frac{HHV_{product} + H_{sensible\ product}}{HHV_{biomass} + H_{steam\ input} + Q_{in}} \tag{2.35}$$

$$\eta_{cold\ gas} = \frac{HHV_{product}}{HHV_{biomass} + H_{steam\ input} + Q_{in}} \tag{2.36}$$

Energy of biomass is the characteristic of feedstock material, which is determined through the ultimate analysis combined with Eq. 2.19. Energy of steam input is found in thermodynamic references (steam table) and energy of syngas can be estimated from Eq. 2.37- 2.40, where n_i and

x_i represent molar rate and mass fraction of the i^{th} component of syngas (J. M. Smith, 2005; Lars Waldheim, 2001).

$$HHV_{syngas} = \sum_{i=1}^{syngas\ components} x_i \,.\, HHV_i \tag{2.37}$$

$$\Delta H_{sensible\ syngas} = \sum_{i=1}^{syngas\ components} n_i . \Delta H_{sensible\ (i)} \tag{2.38}$$

$$\Delta H_{sensible_{(i)}} = \int C_{P_{(i)}} \,.\, dT \tag{2.39}$$

$$C_{P_{(i)}} = a + bT + cT^2 + dT^3 \tag{2.40}$$

Chapter 3 : Continuous biodrying technology for gasification

3.1. Critical review and gaps in the body of knowledge

Successful works of the biodrying of mixed sludge for boiler application encouraged continuing the study of biodrying process for other biomass types and its applicability for other thermochemical processes. Therefore, gasification (in the biorefinery context) was selected as the new application of biodrying process mainly because of the following reasons:

- Recent significant technological developments
- Potentials to address the energy security and climate change concerns by producing a wide range of chemicals and fuels in the downstream, from renewable sources
- Dewatering is an important challenge at the pre-treatment step for obtaining high quality syngas
- Different types of biomass can be used as feedstock

Study of biomass biodrying for gasification was started by critical analysis of the previous studies, where (Kenneth Michael Frei, 2004), (Navaee-Ardeh, 2009) and (Tchoryk, 2011) had reported the results of mixed sludge biodrying for boiler application. Mixed sludge was biodried to 45% moisture level (in the best case) that was sufficient for efficient combustion in the biomass boilers, and techno-economic analysis was performed to assess its economic performance. In the former studies, the generated mixed sludge of the pulp and paper process had directly been disposed in the biomass boiler. Such boilers were receiving high moisture content biomass where supplement fuel maintained the efficiency of boilers high; therefore, no drying system existed before the integration of biodryer.

Implementation of the continuous biodrying technology before combustion boilers could increase the calorific value of sludge, which ultimately lowers the consumption of supplement fuels in the boilers. Therefore, the source of benefit from implementation of biodrying for boiler application was increased calorific value of biomass and the corresponding economic benefit from boiler's operating cost. The winning conditions for successful biodrying for boiler application depended on the dryness level increase of the mixed sludge biomass in the biodrying reactor. Higher the dryness level increase, higher the economic benefit from cost saving of the supplement fuel in the boiler. Comparing the gasification process, a drying unit is mandatory in the pre-treatment step

for obtaining high quality syngas. 45% moisture level of the former studies is not enough for gasification and for acceptable performance of gasifier the moisture must be kept below 20% (Ryan M. Swanson, 2010). Development of the continuous biodrying technology for commercial thermochemical applications is very recent and thorough literature review revealed that its economic viability for gasification has nowhere been addressed. Therefore, the following gaps in the knowledge of biodrying for such application have been determined:

- Source(s) of benefit(s) from biodrying technology for gasification process were unclear
- Applicability of the biodrying technology for gasification process was an important unknown, since the lowest moisture level of the previous studies was 45%
- The winning conditions for successful biodrying in conjunction with gasification in the biorefinery context were also an important unknown
- No thorough and systematic biodrying cost assessments were found
- No profitability assessments for continuous biodrying technology for gasification application were found in the previous studies

Besides, the technical feasibility of biodrying depends of various parameters highlighted by detail at literature review (see section 2.4.3 and section 2.4.4). Among them, sufficient nutrient in the biomass is one of the key requirements for successful biodrying. Each biomass material has inherently unique nutrient level, for instance the nutrient level of pulp and paper mixed sludge is often in the proper range for microbial activity mainly because of high nitrogen (nutrient) content of the secondary sludge. On the other hand, other biomass types such as bark, fibers and other lignocellulosic biomass used in gasification as feedstock, contain very low nutrient level due to little nitrogen content.

Therefore, the feasibility of biomass biodrying in the continuous reactor has been another important unknown, since the availability of nutrient is a key factor. Thorough investigations in the literature revealed that biodrying of lignocellulosic biomass with addition of extra nutrient for adjusting nutrient level had nowhere been studied and no reports were found.

3.2. Hypotheses

Feasibility of biodrying has already been demonstrated at École polytechnique de Montréal using a vertical pilot scale reactor, for the application of mixed sludge. However, considerable uncertainties still exists in terms of whether such technology is feasible for biomass application in conjunction with gasification, in the biorefinery context. The reason of such uncertainties is low nutrient level of the typical lignocellulosic biomass used as feedstock in the gasification-based biorefinery processes. It is believed that by adding nutrient to low-nutrient biomass it is feasible to create the conditions where exothermic aerobic biological activity takes place and biodrying is technically feasible for biomass intended to feed into gasification technologies.

On the assumption that biodrying of low-nutrient biomass is technically feasible, then the technology may or may not be economically viable in conjunction with gasification. From previous works it is known that many operating parameters of biodrying such as residence time, final dryness level, need for removing bound moisture and etc. can affect its economic viability in combination with gasification process at biorefinery context. So it is believed that a techno-economic model can be developed to identify the required performance of the biodrying reactor in order to be economically viable option in combination with gasification.

Therefore, as the main hypothesis of this project, it is strongly believed that biodrying of biomass in conjunction with gasification in the biorefinery context is technically feasible and economically viable.

3.3. Objectives

The following objectives have been targeted in the project:

- Finding the conditions that make the continuous biodrying system technically and economically a viable technology in conjunction with gasification-based biorefinery, which reflects the winning conditions implemented at retrofit with pulp and paper mills
- Investigating the technical feasibility of biomass biodrying by experimental tests
- Investigating achievable final dryness level of biomass before process optimization

3.4. Overall methodology

This work consists of the economic viability assessment of the continuous biodrying technology, followed by technical feasibility verification through experiments. A preliminary techno-economic analysis is performed at the beginning in order to address the first objective. Such analysis principally aims to identify the conditions that make the continuous biodrying system viable in conjunction with gasification process, in the biorefinery context. Then the feasibility of biomass biodrying is investigated by a couple of experimental tests. The following overall step-wise methodology (Figure 3.1) has been developed to address the objectives:

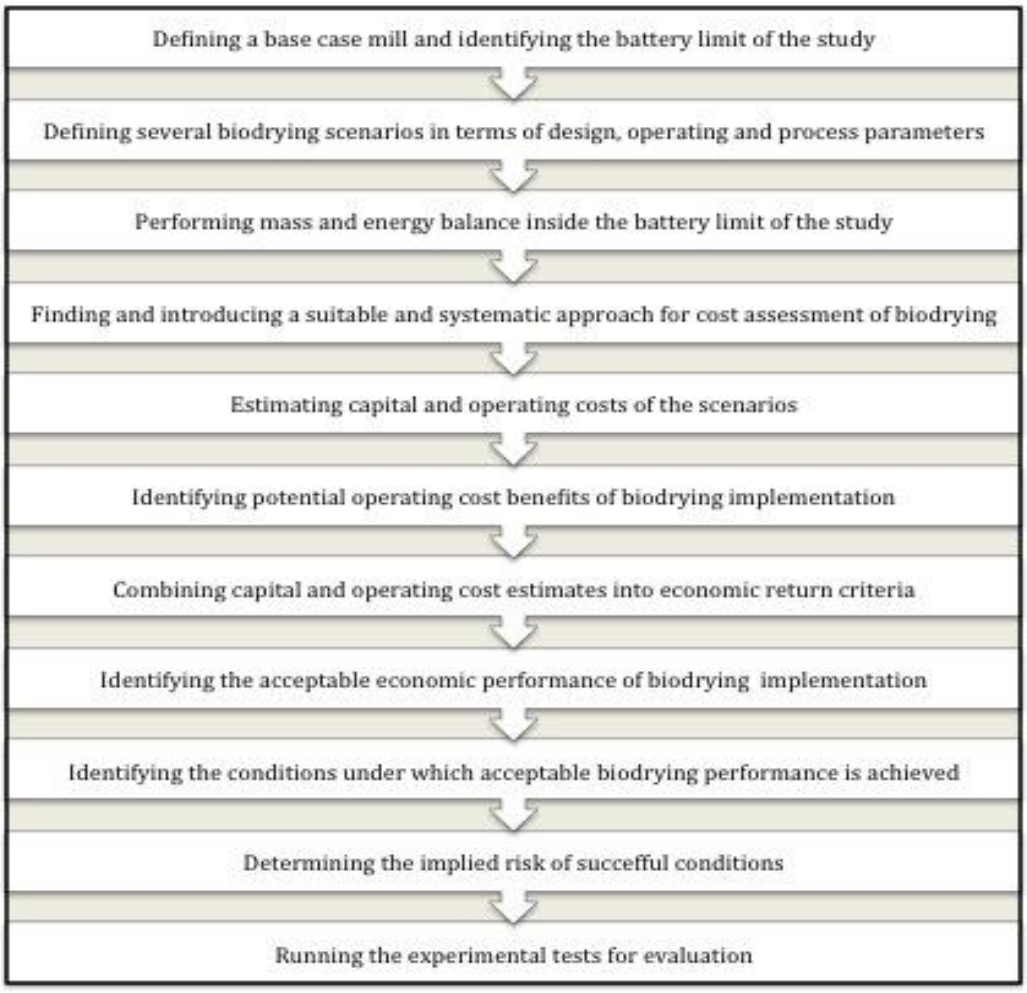


Figure 3.1. Overall step-wise methodology developed for feasibility assessment of biomass biodrying in gasification-based biorefinery process

3.5. Preliminary techno-economic analysis

3.5.1. Base case mill

It is usual to foresee the integration of synfuel production process to existing pulp and paper mills (Fagernäs et al., 2010). In this work, since no industrial partner has been involved, a hypothetic mill is defined as base case for techno-economic assessment based on the previous studies and the available data in the literature. As illustrated in Figure 3.2, an existing pulp and paper mill (Tembec) is considered where TRI gasification process has already been integrated to produce biofuels from biomass via Fischer-Tropsch (FT) process. So, it is assumed that TRI gasification followed by FT process has already been integrated to Tembec pulp and paper mill to produce FT fuels from 500 dry ton per day biomass. Data of the biofuel production process is collected from AMEC document that has balanced mass and energy of the process in 2010 for Wisconsin Rapids mill ("Project Independence Study: Liquid fuels from bimoass, feasibility study - Scope and estimates," 2010). Data of the Tembec mill is collected from Ken Frei thesis (Kenneth Michael Frei, 2004) submitted to École Polytechnique de Montréal in 2004.

Tembec pulp and paper process generates 60m^3 wastewater per each ton of paper, which must be decontaminated to the standard levels before being sent off to the environment. Therefore, it is first treated at primary sludge treatment unit where 70 dry ton per day primary sludge (fibrous residues) are generated. The waste stream is then treated in the activated sludge treatment (AST) basin to reduce the organic content (measured as BOD), which generates 30 dry ton per day of secondary (activated) sludge. Mixed sludge composed of these primary and secondary sludge is formed in a blending chamber and its moisture content is reduced to 74% by mechanical dewatering, before disposal. Power boiler and landfilling are available disposal options where 16% of the mixed sludge is landfilled and the remaining 84% is disposed in the power boiler for energy recovery. Power boiler consumes 300 ton per day wood waste (50% moisture content) as biomass fuel and 22,000 Nm^3 per day natural gas as supplement fuel for steam production. In the biofuel production process, biomass with characteristics mentioned in the Table 3.1 enters to pre-treatment unit where the size is primarily reduced to less than 1/4 of inch by two disc shredders. Then, it enters to drying unit where superheat steam dryer dries the biomass down to 15% moisture level the appropriate range for gasification process.

Table 3.1. Characteristics of biomass used in the biofuel production process

Biomass type	Bark & wood waste
Initial moisture content	50%
Bulk density	300 kg/m^3
Elemental Analysis:	
C	49%
H	5.7%
O	40%
S	0.03%
N	0.01%
Inert & ash	5.2%

Dried biomass enters TRI gasifier, which is a carbon steel refractory lined rectangular vessel (see section 2.6.7). Alumina oxide is used as bed media and the reactor is fluidized with superheat steam injected at 240 °C and 12 bar through fluidizing grid that is installed at the bottom. Endothermic heat of steam reforming reactions is supplied through four pulse combustors that are fully submerged in the fluidized bed. Heaters are standard TRI design configuration. Syngas production rate is 32,600 cubic feet per minute at 29 psig and 1500 °F (820 °C) with the volumetric composition mentioned in Table 3.2 (Newport et al., 2012). Syngas is cooled at heat recovery steam generator (HRSG) unit, tars and impurities are removed consequently and clean syngas enters the Fischer-Tropsch process where 10500 gallon per day wax, 11500 gallon per day diesel, 1300 gallon per day gasoline along with 500 ton per day unreacted syngas (tail gas) with composition mentioned in Table 2.1 and estimated overall energy of 31 MW_{th} (LHV) are produced. Tar is conveyed back to carbon trim cell (CTC) of the gasifier and cracked and the tail gas is consumed in the process to supply the required energy of gasifier and steam dryer. 12.5 MW_{th} of the tail gas is combusted at air heater to boost the temperature of the pulse combustors' flue gas for super-heater of the dryer, 18.3 MW_{th} is sent to PC heaters to supply a portion of the needed energy for reforming reactions. As supplement fuel, 3.1 MW_{th} natural gas with composition mentioned in Table 3.2 is fed to the gasifier. Block flow diagram of the base case mill has been sketched in Figure 3.2.

Table 3.2. Compositions of produced and consumed gases in the biofuel production process in the base case mill

Syngas Composition (mole%)		Tail Gas Composition (mass%)		Natural gas composition (vol%)	
CO	21%	CO	13%	CH_4	89%
H_2	40.6%	H_2	1.5%	C_2H_6	5.2%
CH_4	9.9%	CH_4	6.5%	C_3H_8	1.9%
C_2H_4	1.3%	C_2H_4	2%	C_4H_{10}	0.7%
C_2H_6	0.7%	C_2H_6	0.5%	C_5H_{12}	0.4%
CO_2	24.3%	C_3H_6	0.4%	C_6^+	0.02%
N_2 & inert	1.8%	CO_2	71%	He	0.06%
		N_2 & inert	5%	N_2	2.7%

3.5.2. Biodrying scenarios

Biomass capacity, biomass bulk density, biodrying reactor's volume, residence time of biomass in the reactor, biomass loss and airflow rate are the parameters that affect the cost of continuous biomass biodrying. Biomass capacity and bulk density are defined based on the data of the base case mill (see section 3.2.1) to 500 odt/d[1] and 300 Kg/m^3, respectively. The following scenarios have been considered for capital cost estimations:

- Residence time: 3, 4, 7, 10 days
- Reactor's volume: is the function of both dimensions (depth, width, height) and the residence time. Dimensions of full scale biodrying unit is considered from the previous works accomplished by (Tchoryk, 2011). He recommended three days residence time and 28 m^3/hr per each cubic meter of reactor as the best biodrying conditions and then suggested the following scale-up for commercial applications, based on that:

  Height = 5 m (1.67m per each day residence time)
  Width = 3 m
  Depths = 20 m
  Volume = 300 m^3

[1] Oven dry ton per day

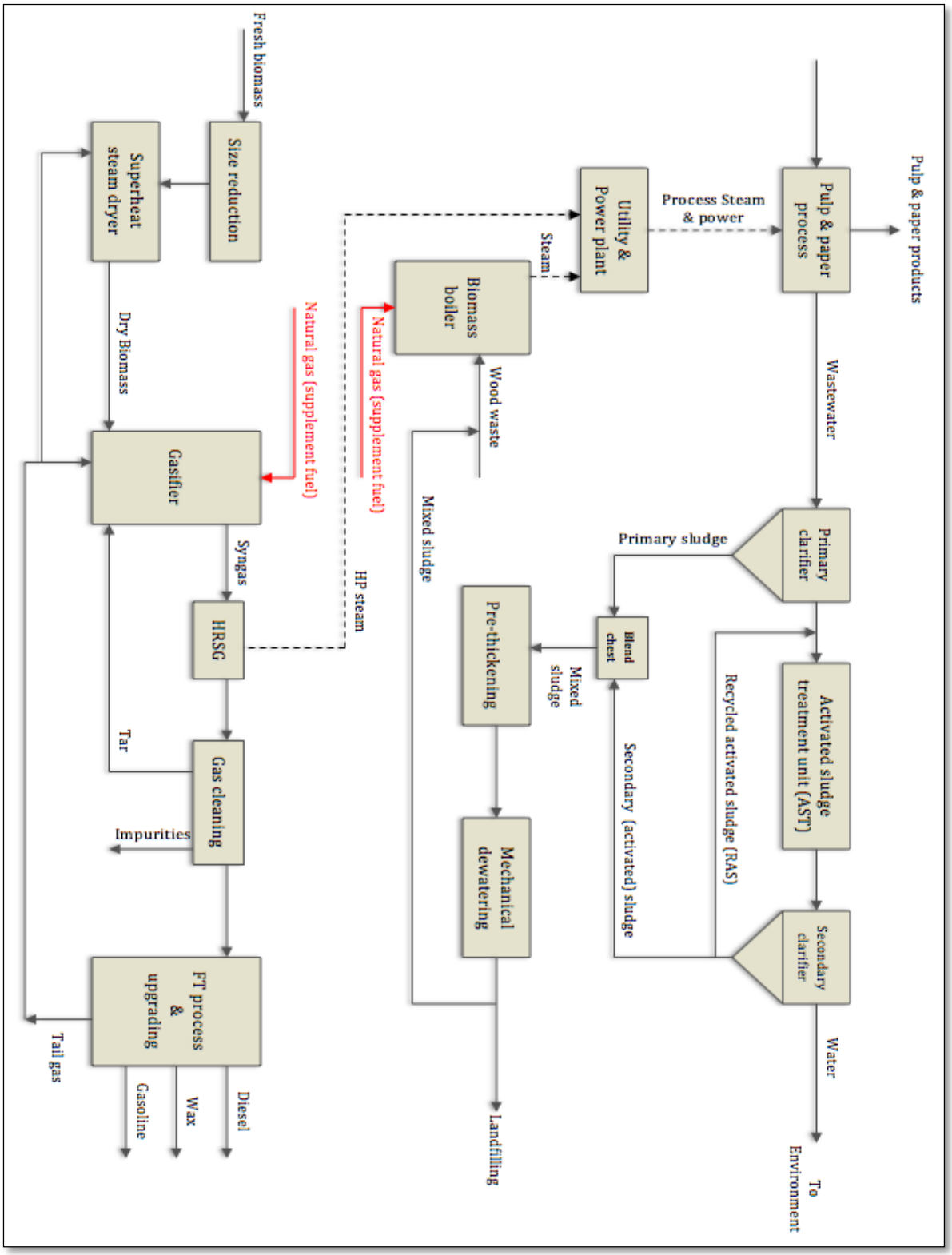


Figure 3.2. Schematic of base case mill process before implementing the biodrying system

Height of the reactor is the direction that biomass moves from top to bottom, width is the direction of airflow and the other (third) direction is the depth (see Figure 4.1 and Figure 4.2). Drying variations in biodrying are in the height and width directions, which correspond to residence time and pneumatic conditions, respectively. Depth of the reactor is the only dimension along which there is no drying variation (Kenneth Michael Frei, 2004). Therefore, depth can represent reactor's volume and in addition to 20m scenario suggested by (Tchoryk, 2011), 50m is also considered among the scenarios.

In terms of operating cost, further to abovementioned scenarios, the following were also considered:

- Biological loss has been reported to be in the range of 5-18% (Shahram Navaee-Ardeh, 2010), therefore 5%, 10% and 20% carbon loss due to biomass degradation has been considered among the scenarios
- Airflow requirement: 28, 20 m^3/hr per cubic meter of the biodrying reactor

3.5.3. Systematic cost assessment approach for biodrying cost estimations

Reliable estimate of fixed capital investment and operating costs are essential for either techno-economic evaluation or equipment selection when analyzing a system or comparing different technologies. Information of the equipment and process costs are usually remained confidential in the industry, and it will practically be very difficult to find a precise costing in the literatures resources, so it is essential to use shortcut methods to quicken the estimates on fixed capital investment (FCI) and operating costs (Kudra).

Cost assessment for drying processes follows the well-known method widely used in the process industries. Systematic approach and different steps of preliminary estimation of any drying systems are schematically shown in Figure 3.3. Once the purchased costs of drying system are estimated then the installed cost, other fixed costs, and ultimately fixed capital investment are estimated using factor method. A drying reactor itself is only one component of a drying system, so fixed capital investment and operating cost must be estimated for whole of the drying process in the plant.

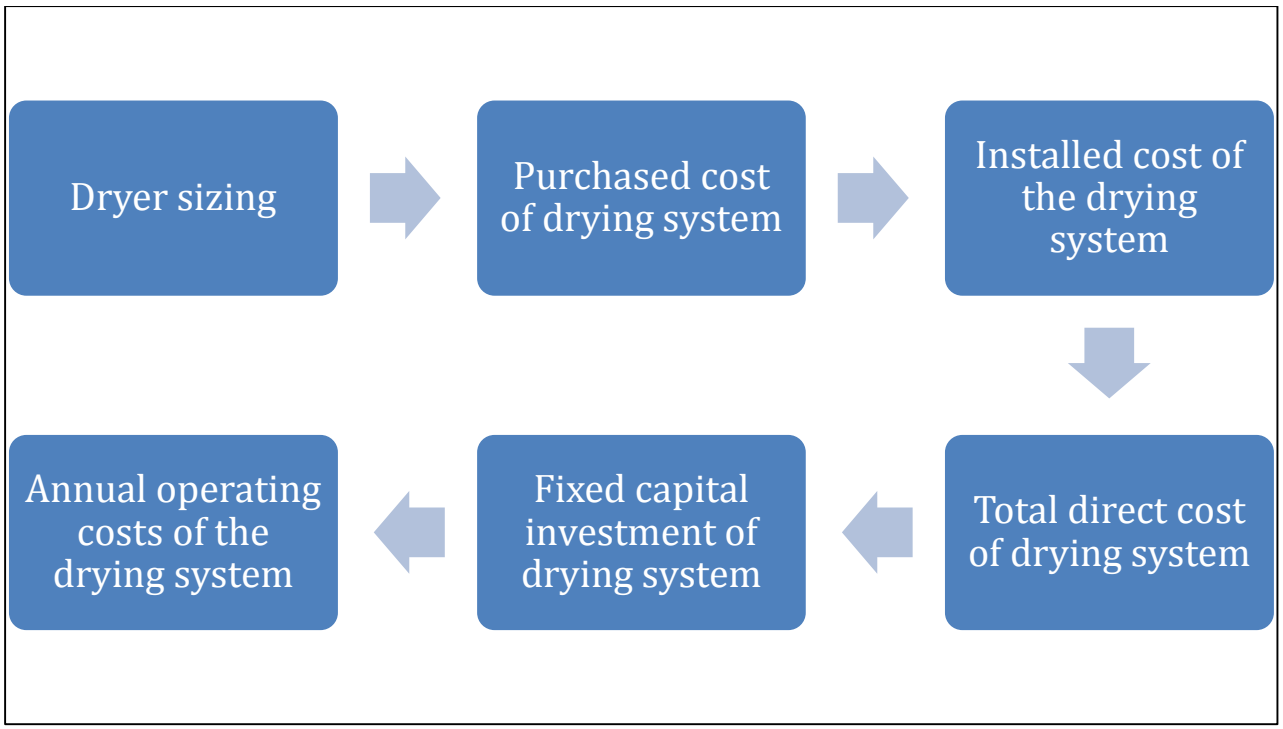


Figure 3.3. Cost estimation steps for drying systems

3.5.4. Purchased cost of the drying systems

One of the most common purchased cost estimation methods is using the data of related literatures. These data are often related to technical and economic conditions of the past that might be considerably different from the actual situation. Capacity and inflation rate are the ones that are usually different in various cases, so the following steps are taken for estimation:

- Updating the former cost to actual cost
- Scaling-up or scaling-down the former capacity to desired capacity

3.5.4.1. Updating the former cost to actual cost

Due to inflation and inevitable fluctuations in the economy, costs and equipment prices are always subjected to change. The methods called “Chemical Engineering Plant Cost Index” (known as CE index) and “Marshal and Swift All-industry Equipment Cost Index” (formerly known as Marshal and Steven cost index) are two most commonly used for covering the inflation and updating the costs (Kudra; Max S. Peters). However, the latter (M&S) has been

recommended for updating high-level process equipment (Kudra). Eq. 3.1 is formula that has widely been accepted for equipment cost updating using M&S cost index, and Table 3.3 shows indices used there.

Updated cost= Original cost in literature × (Marshall & Swift index at updated time / Marshall & Swift index at the time of original cost) (3.1)

Table 3.3. Marshall & Swift all-industry equipment & Chemical Engineering Plant cost index (1989-2004) (Kudra)

	M&S Index	CE Index
1989	895.1	355.4
1990	915.1	357.6
1991	930.6	361.3
1992	943.1	358.2
1993	964.2	359.2
1994	993.4	361.1
1995	1027.5	381.1
1996	1039.2	381.7
1997	1056.8	386.5
1998	1061.9	389.5
1999	1068.3	390.6
2000	1089	394.1
2001	1093.9	394.3
2002	1104.2	395.6
2003	1123.6	402
2004	1178.5	444.2

3.5.4.2. Scaling-up/down of cost to the desired capacity

For drying systems (or any other process equipment), cost of the same dryer types with different capacity is roughly predicted by following empirical equation (Eq. 3.2).

$$Predicted\ cost = original\ cost \times \left(\frac{desired\ capacity}{original\ capacity}\right)^{n} \quad (3.2)$$

Desired capacity is actual capacity and original capacity is the capacity of the same dryer (or any type of equipment) where the cost is known. Exponent "n" has different values in different equipment, which are available in the references. If the value could not be found in any literature

sources then n=0.6 can be taken for very rough estimation. Some examples of the ‘’n’’ value for equipment used in the drying systems have been listed in Table 3.4.

Table 3.4. Exponent “n” relating some equipment cost to capacity (Kudra)

Equipment type	Capacity range	Exponent “n”
Cyclone	0.01-4 m^3/s	0.61
Dust collector	1-470 m^3/s	0.78
Venturi scrubber	3.3-38 m^3/s	0.46
Roll crusher	3-66 kg/s	0.97
Belt conveyor	5-19 m^2	0.50
Screw conveyor	0.4-0.8 m^2	0.53
Pan dryer	1-19 m^2	0.50
Vacuum shelf dryer	1.4-92 m^2	0.54
Tunnel dryer	2-10 m^2	0.50
Roto-Louvre rotary dryer	4-93 m^2	0.62
Multiple cyclone	4-94 m^3/s	0.66

3.5.5. Installed cost of the drying systems

Installed cost of a drying system (or any other equipment) consists of purchased cost of the system plus freight, assembly and installation, cost of piping, wiring, instrumentation and control system. These costs can be estimated based on the vendors’ data, previous known costs (less accurate), or factor method. By using factor method, the following should be considered:

- Assembly, piping, wiring, instrumentation and control system
  - Fully equipped compact system: 25%-30% of the purchased cost of the drying system
  - Fully equipped system delivered in many parts: 40%-45% of the purchased cost of the drying system

- Freight: 7% of the (purchased + assembly, piping, etc.) costs

3.5.6. Total direct plant costs of the drying systems

Total direct plant cost of drying systems (TDC) is higher than the installed cost. There are few additional charges to establish a drying system in the plant, as below:

- Buildings:

  - If the drying system is installed inside a building the cost will be 20%-35% of the installed cost
  - If the drying system is installed outside a building the cost will be 15% of the installed cost
- Utility supply, site development, and other direct expenses will be around 20%-40% of the installed cost

3.5.7. Fixed capital investment of the drying systems

For obtaining the fixed capital investment (FCI) of a drying plant following items should be added to the costs:

- Contractor's fee: 10%-27% of the direct plant costs (TDC)
- Insurance, customs, taxes, land: 7% of the direct plant costs (TDC)
- Contingencies: 10%–30% of the direct plant cost (TDC)
- Procurement, supervisory, administration, and other owner expenses related to the plant: 5%–15% of the direct plant cost (TDC)

3.5.8. Operating cost of the drying systems

The last step in cost estimation of any drying process is operating cost estimations. Maintenance cost, lost or degraded raw materials, labor and utility are costing elements of the drying systems.

3.5.8.1. Maintenance cost

Maintenance cost is estimated based on the factor method. For complex conventional drying systems contain explosive or toxic raw materials with several rotating and vibrating items, 10% of the fixed capital investment (FCI) and for simple conventional systems 5% have been suggested (Kudra). Since biodrying system does not include many vibrating and rotating devices and biomass feedstock is non-toxic and it is not classified as dangerous materials, 3% can be acceptable. This is in agreement with Tchoryk's recommendation as 2% (Tchoryk, 2011) in the previous study.

3.5.8.2. Lost or degraded raw materials

In the conventional drying technologies, small portion of the raw material is lost due to the elevated heat used to dry biomass. Thermal destruction of biomass starts at around 150°C where hemicelluloses are destroyed and loss is accelerated rapidly when temperature is raised (Fagernäs et al., 2010). In the biodrying process there is not such temperature rise but instead, a portion of

biomass is lost due to the degradation of organic fraction of biomass by bacteria (see section 2.4.3). These losses should be compensated by auxiliary raw materials that add up the annual costs.

3.5.8.3. Labor cost

Unit cost of the labor should be in compliance with local economy and must include insurance, taxes, and social charges. Labor cost of the drying systems depends on the mode of process. The cost in batch systems depends on the: quantity of handled materials, type of the employed equipment, and schedule of the plant's operation that can be roughly estimated as 2 man-hour/(m^3 of dried material)+1/3 man/dryer/shift (Kudra). But in the continuous drying systems labor activities are restricted to supervision of the control panels, feeding and discharge systems, which lowers the labor cost compared to the batch systems (Kudra). Operator requirements per unit per shift for different types of process equipment are found in Table 3.5 (Ulrich, 1984).

Table 3.5. Estimation of operator requirement for different types of process equipment (Ulrich, 1984)

Equipment type	Operator/ unit/ shift
Boilers	1
Cooling towers	1
Wastewater treatment plants	2
Evaporators	0.3
Fans	0.05
Blowers and compressors	0.1-0.2
Gas-solid contacting equipment [(b)]	0.1-0.3
Heat exchangers	0.1
Bag filters	0.2
Storage vessels	-

[(a)] coolers, dryers, fluidized beds, roasters

Biodrying process comprises drying columns where biomass is in contact with air that is blown by blowers, so it is estimated that process would require one fifth (0.2) of the attention of an operator to control the systems and handle the process. Thus, 1/5 man/unit/ shift can be roughly estimated as the labor cost for biodrying process.

3.5.8.4. Utility cost

Electricity, process steam, compressed air, cooling water, demineralized (boiler feed) water, etc. are typical utilities. Among them, biodrying system implemented to a gasification process only requires electricity and air. Blowers are electricity consumers that supply air for the aerobic activity. Air is required for the instruments. Power requirement of blowers is obtained from Eq. (3.3) with assumption of isothermal air compression (Warren L. McCabe, 2005):

$$Power\ (kW) = \frac{1.97 \times T_a \times q_0}{\eta}\ \ln\left(\frac{P_b}{P_a}\right) \qquad (3.3)$$

Where T_a is ambient temperature in Kelvin, Q_s is airflow rate at standard condition ($0^{\circ}C$ and 1 atm), η is blower efficiency, P_b is the blower discharge pressure depends on the pneumatic condition of the biodrying unit, and P_a is atmospheric pressure.

3.5.9. Effect of biomass moisture level on TRI gasification process

A significant drawback of biomass gasification compared to direct combustion is the limitation in the feedstock quality especially in terms of moisture content. Several works have reported moisture content as a typical problem while gasifying biomass. Freshly cut biomass has moisture level of 30%-60% (De Filippis, Borgianni, Paolucci, & Pochetti, 2004; Kei Yamashita, 2004) that has been reported too high for any gasification technologies. In an experimental work on a bubbling fluidized bed (Kaewluan & Pipatmanomai, 2011) reported that gasification at moisture content > 30% is not operatable. Thus, the pre-treatment of biomass is mandatory in gasification to reduce the moisture content to the acceptable level. Gasification, generally has four stages Drying, Pyrolysis (de-volatilization), Volatile combustion & char oxidation, Steam reforming /gasification of char (Li et al., 2004; J. Xu & Qiao, 2012). Moisture plays an important role on the performance of gasification process. It has significant influence on the drying step that affects the subsequent de-volatilization step. Drying and pyrolysis steps consume heat in the gasifier and cause gas temperature to decrease. Although higher moisture increases the concentration of water at char particle surface (pyrolysis step), which is apparently ideal for steam reforming, but on the other hand it absorbs heat and reduces particle and gas temperatures and lowers the de-volatilization and surface reaction rates. More volatile combustion or char oxidation is then

required to stabilize the temperature and supply the required energy for endothermic reactions (J. Xu & Qiao, 2012). De-volatilization (evolution of volatile matters) is a two-step process takes place at steam reformer (J. Xu & Qiao, 2012):

1) First step yields tar, primary volatile gases (CO, H_2, CH_4, HCN, etc.), and residual char
2) In the second step, tar is transformed to the secondary volatile gases (CO, H_2, CH_4, HCN, etc.).

Thus, higher moisture reduces the reaction temperatures and hence it deteriorates the performance of gasifier. It drops the temperature due to the latent heat of vaporization and principally targets the second de-volatilization step where tar cannot be cracked and transformed to secondary volatile gases. As a result, tar content of syngas increases, gas yield decreases, and composition of syngas is affected (Ian Narvaez, 1996; Javier Gil, 1997; José Corella, 2008; Kaewluan & Pipatmanomai, 2011; Lv et al., 2004).

3.5.10. Temperature drop and tar content of fluidized bed gasifier in various biomass moisture levels

Simulation or mathematical modeling of gasification process is out of the scope of this project, therefore rough estimations based on the experimental data of literature for similar technologies were made to understand how much temperature and tar content is varied in different moisture levels.

3.5.10.1. Temperature of the fluidized bed in different moisture levels

(Kaewluan & Pipatmanomai, 2011) gasified rubber woodchips containing different moisture levels in a 100 kW_{th} fluidized bed reactor and recorded the bed temperatures. They reported the initial temperature of 760°C that is decreased by about 60°C while raising the moisture level of biomass from 9.5% to 25.5%. On the other hand (Jarungthammachote & Dutta, 2007) have thermodynamically modeled a biomass gasifier and reported linear temperature decrease by increasing moisture content. Therefore, it can be estimated that each 10% moisture roughly diminishes 35°C of the gasifier's bed temperature. TRI gasifier is designed to work at 820°C in the base case (see section 3.5.1) ("Project Independence Study: Liquid fuels from bimoass, feasibility study - Scope and estimates," 2010) while receiving biomass with moisture around 15%, so temperature decrease is roughly estimated as in Table 3.6.

Table 3.6. Estimation of TRI bed temperature in different biomass moisture contents

Moisture Content	Bed Temperature (°C)
15%	820
25%	785
35%	750
45%	715
55%	680
65%	645

3.5.10.2. Gas yield in different moisture levels

(Kaewluan & Pipatmanomai, 2011) measured the gas yield in moisture levels between 9.5% and 25.5% and reported it as mentioned in Table 3.7. Since no were found for higher moistures, this table is extrapolated for very rough estimation of gas yield at moistures higher than 25.5% (Figure 3.4).

Table 3.7. Gas yield of a 100 kW_{th} gasification reactor [adapted from (Kaewluan & Pipatmanomai, 2011)]

Moisture Content	Gas Yield (Nm^3/Kg dry biomass)
9.5%	2.08
18.1%	2.02
25.5%	2.00

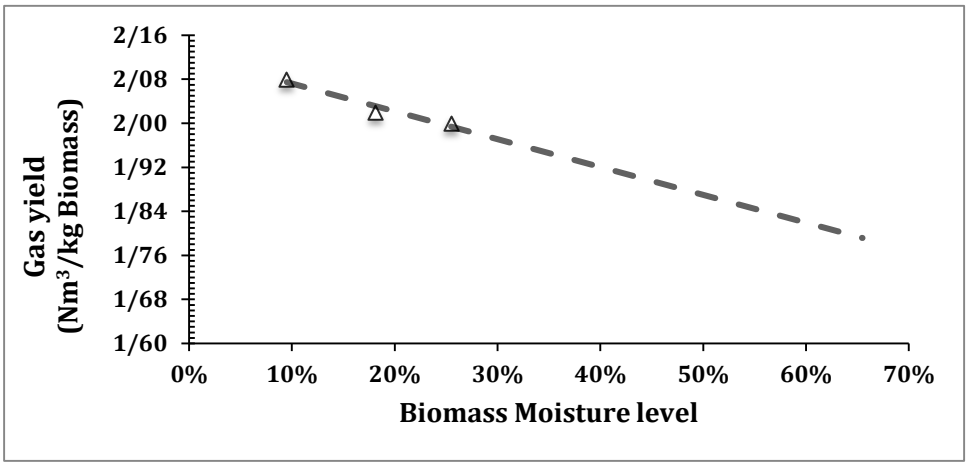


Figure 3.4. Gas yield estimation of a fluidized bed gasifier in different biomass moisture levels

It is estimated that for each 10% moisture increase, the gas yield is roughly decreased around 4%. Since TRI gasifier is fluidized bed and it is flexible in terms of feedstock (see section 2.6.7) such estimation can be applicable. Gas yield at the base case was calculated from the results of mass and energy balance performed by AMEC ("Project Independence Study: Liquid fuels from bimoass, feasibility study - Scope and estimates," 2010), which is 1.98 Nm^3 per kg of dry biomass while having 15% moisture content. Table 3.8 shows the gas yield estimation in different biomass moisture levels.

Table 3.8. Estimation of TRI gas yield in different biomass moisture levels

Moisture Content	**Gas Yield (Nm^3/Kg dry biomass)**
15%	1.98
25%	1.90
35%	1.82
45%	1.74
55%	1.67
65%	1.60

3.5.10.3. Tar generation in different biomass moisture levels

TRI Corp. reported in average 4.1 grams tar generation per each normal cubic meter of the syngas (range of 1.9-6.3), measured at 4 dry ton per day biofuel demonstration unit (PDU) constructed in Durham, North Carolina (Newport et al., 2012).

On the other hand, (Pfeifer, Koppatz, & Hofbauer, 2011) gasified woodchips at 100 kW fluidized bed gasifier in the temperature range of 810-850 °C by using steam as gasifying agent, and reported the quantity of tar in 6%-40% moisture levels, shown in Figure 3.5. Since no further data were found for higher moisture contents, extrapolation was used to estimate the tar content at higher moisture levels (Figure 3.6).

At 15% moisture, tar content of syngas reported by (Pfeifer et al., 2011) is nearly the same as the one TRI has reported. Furthermore, his working temperature was in the range of TRI gasifier of the base case (see section 3.5.1), so these data was used to estimate total tar quantity of TRI gasification unit (Table 3.9 and Figure 3.7)

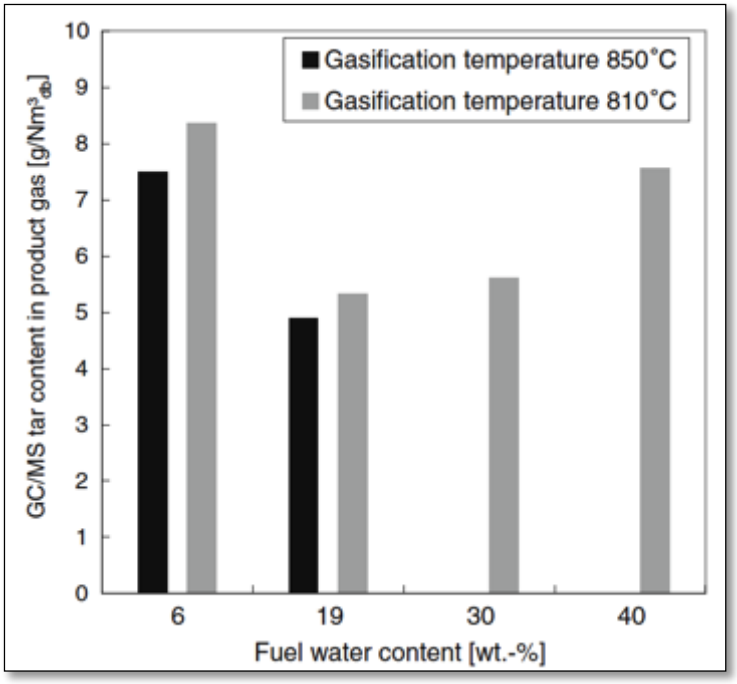


Figure 3.5. Tar generation of a fluidized bed gasifier using steam as the gasifying agent in different biomass moisture levels (Pfeifer et al., 2011)

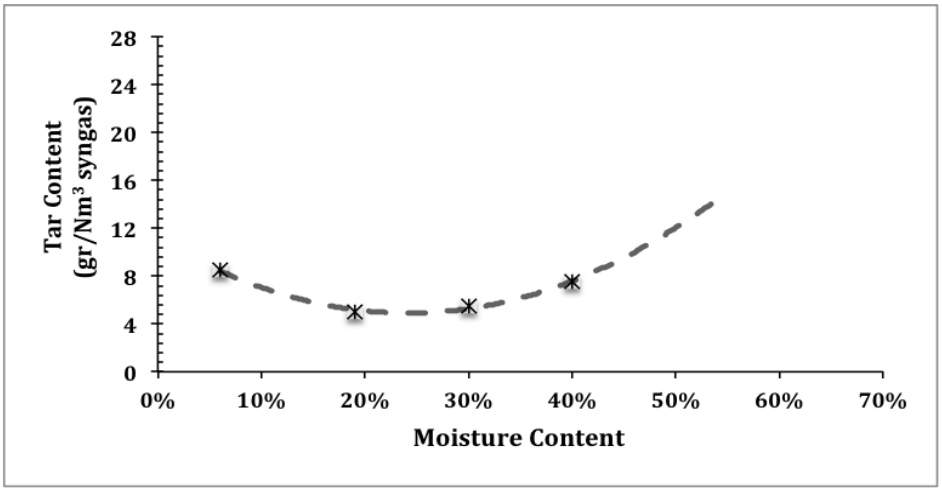


Figure 3.6. Estimation of tar generation in a fluidized bed gasifier using steam as the gasifying agent in different biomass moisture levels [adapted from (Pfeifer et al., 2011)]

Table 3.9. Estimation of the quantity of tar generated per day in different biomass moisture levels at TRI gasifier

Biomass Moisture Content	Specific Tar Content (gr/Nm^3 syngas)	Gas Yield (Nm^3/Kg dry biomass)	Total Tar generation (ton/day)
15%	4.1	1.98	4.0
25%	4.9	1.90	4.7
35%	6.1	1.82	5.8
45%	9.5	1.74	8.2
55%	15	1.67	12.5
65%	22.7	1.60	18

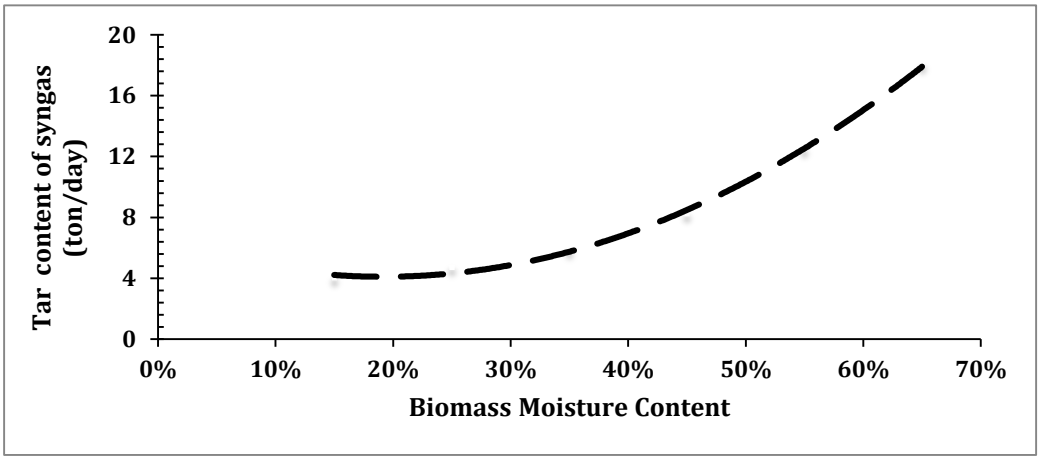


Figure 3.7. Estimation of tar quantity per day in different biomass moisture levels at TRI gasifier

3.5.11. Short discussion (2)

In the gasifier, moisture increase affects the energy distribution in the drying and pyrolysis zones and it ultimately decreases the temperature of gasifier, which affects the gasification stage and tar cracking reactions that take place at high temperatures. Therefore, moisture increase causes more tar generation in the process. It is estimated that the quantity of tar is exponentially raised from 4 to 18 ton per day while moisture increases from 15% to 65%. Due to operational difficulties in the downstream of gasification process, tar must be eliminated before Fischer-Tropsch reactor. That's why all of the references have mentioned the required moisture content in the range of 15% (Alauddin, Lahijani, Mohammadi, & Mohamed, 2010; Ian Narvaez, 1996; Javier Gil, 1997; Lavoie, Marie-Rose, & Lynch, 2012; McKendry, 2002; Newport et al., 2012; Robin W. R. Zwart, 2006; Ryan M. Swanson, 2010; Stéphane C. Marie-Rose, 2011; van den Enden & Lora, 2004) before gasifiers. In a tele-meeting held at École polytechnique de Montréal on May 2013, Doug

Freeman, the project manager of NewPage Corp. also confirmed 15-17% biomass moisture level before TRI demonstration unit at Wisconsin Rapids Mill in NC. Therefore, it is confidently concluded that dryness level of biomass is crucial parameter that must be kept at around 15% at pre-treatment unit.

3.5.12. Integration of biodrying process to the base case mill

3.5.12.1. Fixed capital investment of the biodrying system

Based on the systematic approach explained in sections 3.5.3- 3.5.8, the following standard factors (Table 3.10) is chosen to estimate the fixed capital investment of biodrying system, which is implemented at base case mill.

Table 3.10. Factors considered for fixed capital investment (FCI) estimation of continuous biodrying system

Category	Cost description	Cost factor	Reference
Purchased Cost (PC)	Purchased cost of biodrying reactors	Estimation by data of literature (section 3.5.4)	(Tchoryk, 2011)
	Purchased cost of blowers	Estimation by data of literature (section 3.5.4)	(Wouter J.J. Huijgen, 2007)
Installed Cost (IC)	Assembly and installation, piping, wiring, instrumentation and control systems	25% of PC	(Kudra)
	Freight	7% of (PC + assembly)	
Total Direct Plant Cost (TDC)	Building and structures on which biodrying system should be installed	15% of IC	
	Site development, utility supply, other direct expenses	20% of IC	
Fixed Capital Investment (FCI)	Contractor's fee	10% of TDC	
	Insurance, customs, taxes, land, other owner costs	7% of TDC	
	Procurement, supervisory, administration	5% of TDC	
	Contingencies	10% of TDC	

For purchased cost estimations the following steps is taken:

- The number of required biodrying units in each considered scenarios (see section 3.5.2) is calculated
- Cost of each unit at the reference year and reference capacity is extracted from the reliable literature sources
- Marshall & Swift cost index of the reference and target years is applied
- Costs are scaled-up from reference capacity to the actual capacity of the scenarios

Main equipment of biodrying system is the reactors and two blowers for each (see section 3.4.1). Purchased cost of the reactor in $2004 has been extracted from (Tchoryk, 2011) who studied the techno-economic of continuous biodrying for boiler application. He estimated each biodrying reactor would cost M$ 0.17. Blower cost has been reported €10,000 by (Wouter J.J. Huijgen, 2007) for 350 m^3/hr capacity. For actual capacity of the scenarios and $2014 costs, Eq. 3.1, Eq. 3.2, Table 3.3, and exponents (n) 0.6 and 0.59 for reactor and blower respectively, is used to estimate the fixed capital investment of the biodrying system. Number of biodrying unit for 500 ton per day capacity has been shown in Table 3.11 and the capital cost estimates shown in Figure 3.8.

Table 3.11. Number of required biodrying units for 500 dt/day biomass Capacity

20m deep reactor, 300 Kg/m^3 bulk density biomass	17 units
50m deep reactor, 300 Kg/m^3 bulk density biomass	7 units

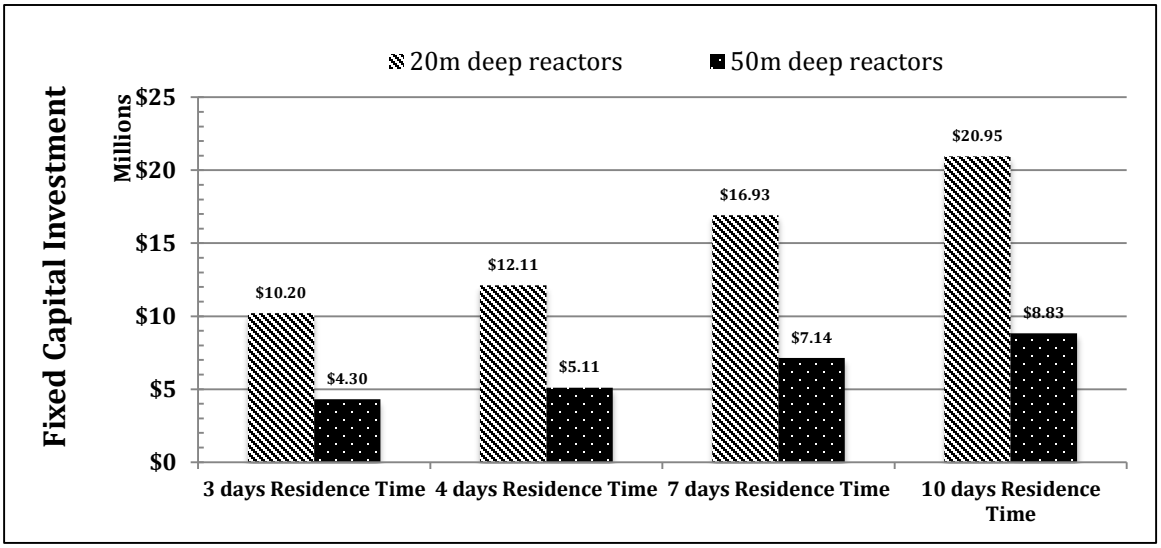


Figure 3.8. Fixed capital investment of continuous biodrying system for 500 dry ton per day biomass capacity

Biodrying units with 50m of depths have lower capital cost compared to 20m deep designs, that's mainly because the number of required biodrying units in 50m designs are much less than 20m designs. Although both designs have higher investment cost compared to rotary dryer with about M$ 3 for the same capacity (Badger, 2002), but the advantage is in operating cost due to the fact that is free from external heating sources.

3.5.12.2. Operating cost estimation of the continuous biodrying system

Maintenance, utility, labor and auxiliary biomass costs are the components of the annual operating cost of the biodrying system (section 3.5.8), which is estimated in each scenario. Residence time, reactor's volume, airflow rate, ambient temperature, blower's efficiency and biological carbon loss of biodegradation are the influential parameters on the operating cost. Using Eq. 3.3 and making the following assumptions estimate the electricity consumption:

- Blower efficiency = 90%
- Ambient temperature= 25 °C
- The equation is valid only if little or no compression work is done on the air, otherwise compressor equations will be required, so 5% compression at discharge is assumed.

For operating cost estimation of the scenarios, the biomass cost is assumed as $25 per green ton (Freeman, 2010), labor cost as $20/hour, power cost as $0.04/kWh (K.M. Frei, 2006). Results (Figure 3.9) show that the same as fixed capital investment shorter residence time lowers the operating costs mainly due to the lower power consumption. Shorter residence time requires less air during the drying period, which reduces the power costs. Higher airflow rate needs more power, and higher biological mass loss imposes more biomass cost to the system. In terms of operating cost, however, biodrying technology remains an attractive option especially at shorter residence times, compared to the conventional dryers that consume external energy by about 3-5 MJ/Kg moisture removed.

3.5.12.3. Benefits from implementing the biodrying system to the base case mill

If biodrying process would successfully be implemented to the gasification-based biorefinery of the base case mill (see section 3.5.1) and biomass is dried to around 15% (the level appropriate for gasification), then the following benefits are predicted for the mill:

- Saving from sludge landfilling
- Saving from OPEX of the power boiler
- Saving from OPEX of the gasifier
- CO_2 gas mitigation
- Increase in biofuel production rate

The secondary sludge of Activated Sludge Treatment (AST) unit (Figure 3.2) is the source of nutrient for activity of microorganisms. By integrating the biodrying system to the base case mill the secondary sludge must be conveyed to biodrying process to provide one of the key requirements of biodrying: nutrient. Removing the secondary sludge from the waste stream facilitates the de-watering of the primary sludge by mechanical devices, which makes it suitable for boiler application. As a result, the primary sludge is disposed in the boiler and secondary sludge is disposed in the gasifier, which reduces the quantity of sludge to landfill area. After integration of biodrying system, 30 dry ton per day secondary sludge is removed from the waste stream and directed to biodrying process.

By employing the combination of forced aeration and biological heat of microbial activity instead of fossil fuel (natural gas), to reduce the moisture content of biomass, the tail gas spent for producing steam in the superheat steam dryer can be used to offset more natural gas in the power boiler and gasifier. In the base case mill, 12.5 MW_{th} of unreacted syngas (tail gas) from Fischer-Tropsch reactor is used to produce steam of dryer. Economy of fossil fuel in the boiler and gasifier mitigates the quantity of CO_2 generated in the mill from fossil sources, which leads cost mitigation.

Disposing the secondary sludge biomass in the gasifier raises the biofuel production rate from the dry mass of sludge, in the Fischer-Tropsch reactor. The mass and energy balance shows that in the biorefinery process of the base case mill 21, 23, and 2.6 gallon wax, diesel, and gasoline, respectively are produced per each ton of dry biomass that enters into the biorefinery process. Therefore, increasing the dry biomass in the process inlet returns higher biofuel production rate at the end of the process. Table 3.12 shows estimation before and after implementation of the continuous biodrying system.

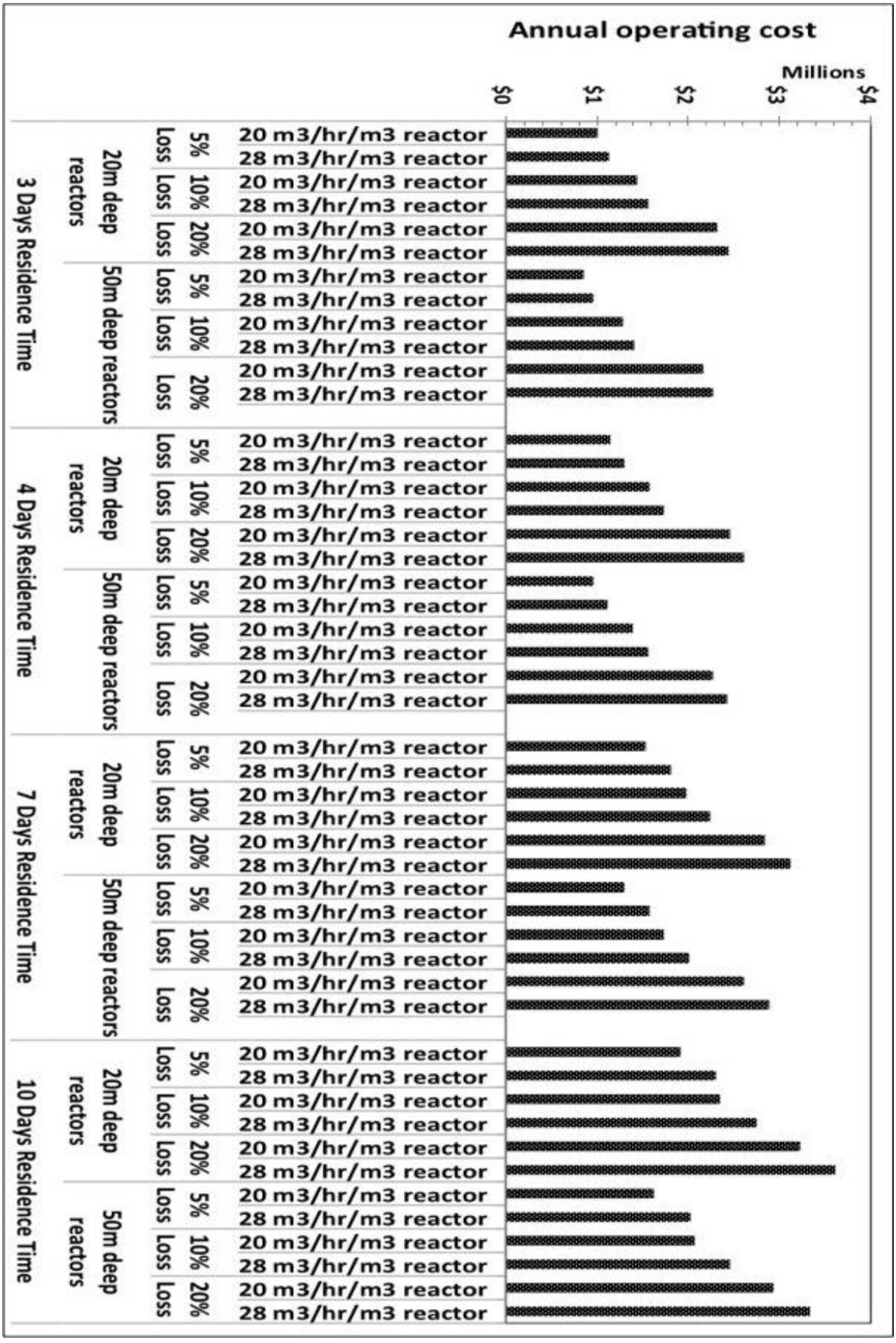


Figure 3.9. Estimation of annual operating costs of biodrying system for 500 dry ton per day biomass capacity

The CO_2 cost for a mill is $10 per each ton of carbon dioxide (K.M. Frei, 2006), natural gas costs $4/GJ (EIA website), landfilling cost is in average $30 per dry ton of sludge (K.M. Frei, 2006). Crude wax is assumed $3 per gallon. Market prices of diesel and gasoline fuels at east coast region in 2014 have been reported as $3.6-$4.2 and $3.2-$3.7 per gallon respectively (Figure 3.10), where 13% tax (for diesel and gasoline) along with 17% marketing and distribution costs for diesel and 10% for gasoline were included (EIA website); thus, the average sales prices of $2.73/gal and $2.70/gal for diesel and gasoline respectively, are assumed for revenue of the mill.

Benefits of implementing continuous biodrying system in the base case mill is depicted in Figure 3.11 where the increase of biofuel production rate from gasifying the dry mass of the activated sludge, is the most important source of benefit that holds 43% of the total share.

3.5.13. Profitability evaluation of the continuous biodrying system

In general, the most common mathematical methods of profitability evaluation are categorized under the following headlines (Max S. Peters):

- Rate of return on investment (ROI)
- Discounted cash flow (DCF)
- Net present value (NPV)
- Payback period (PBP)

Each of these methods has its own advantages and disadvantages and none of them is marked as the best or the worst. An engineer should understand the idea of each method to be able to choose the best saccording to the particular situation.

- ROI: is expressed as percentage that represents the fractional return of money. It is simply the yearly profit divided by total initial investment. It considers the annual average values and doesn’t include the time value of money. It relies on the fact that profit and costs don’t vary significantly over the lifetime of a project.
- DCF: is the amount of investment that is not returned at the end of each year during the estimated life of a project. It considers time value of money and requires trial-and-error

procedure for obtaining the internal rate of return (normal interest or payoff of project) that reduces investment cost (cash flow) to zero.

- NPV: is the difference between the worth of annual cash flow at present time with known rate of return (*i*), and the initial required investment. The rate of return in NPV can be either the minimum acceptable rate or the average rate that company earns on the project.
- PBP: is the minimum length of time theoretically needed for recovering the capital investment. In PBP there are two possible approaches: payback periods excluding and payback period including the interest. In the first approach effect of the interest is neglected and cash flow is simply based on the income minus costs except depreciation, whereas in the latter, annual cash flow is discounted cash flow at designated interest rate that reflects the time value of money.

Here, since the integration of biodrying system to an existing mill is under investigation, fraction of return on the investment is important, therefore, internal rate of return is chosen as the economic indicator and the following assumptions are made or economic analysis:

- 350 operating days per year in the mill
- 20 years project lifetime
- Salvage value of biodryers equal to zero after the lifetime
- 100% equity
- 30% income tax
- Accelerated depreciation that depreciates the equipment by 50% of the cost in the first year, 25% in the second year, and 25% in the third year. Such depreciation approach is widely accepted in the industry.

An existing financial contribution (called IFIT) is considered as well in the profitability evaluations of continuous biodrying system. It is a governmental program that has been created to accelerate the establishment of new technologies in the Canadian forest industry. The program supports the Canadian forest sector to become environmentally sustainable and economically more competitive.

Table 3.12. Mass and energy flows inside before and after integration of the continuous biodrying system

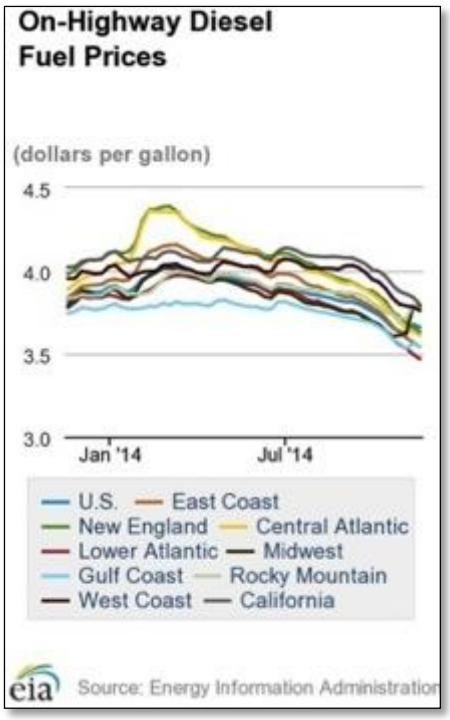
	Base Case	After implementation biodrying process	Increase / Decrease	Remarks
Sludge to landfill	16 odt/d *	0 odt/d	- 16 odt/d	-
Natural gas (power boiler)	22,000 Nm^3/d **	0 Nm^3/d	- 22,000 Nm^3/d	Saving by replacing FT tail gas
Natural gas (PC heaters of the TRI gasifier)	7,700 Nm^3/d	0 Nm^3/d	-7,700 Nm^3/d	Saving by replacing FT tail gas
CO_2 emissions	64 t/d	0 t/d	- 64 t/d	Tail gas is carbon neutral since it is from biomass
Biofuel production	23,000 GPD***	24,500 GPD	+1500 GPD	Diesel, gasoline, and wax from Fischer-Tropsch process

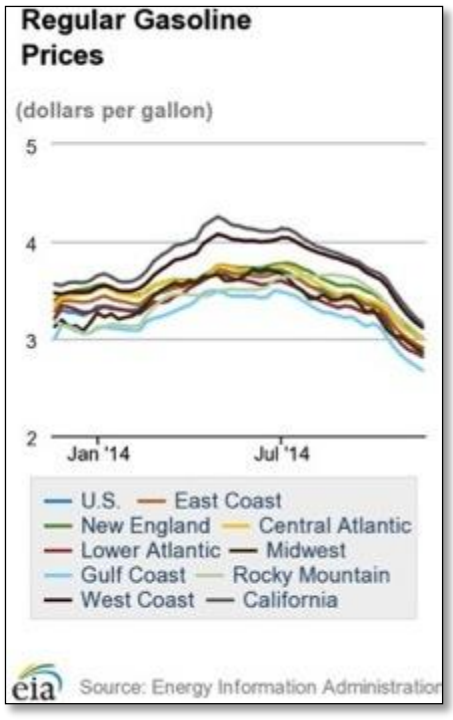
* Odt/d: oven dry ton per day

** Nm^3/d: Normal cubic meter per day

*** GPD: gallon per day

(a)

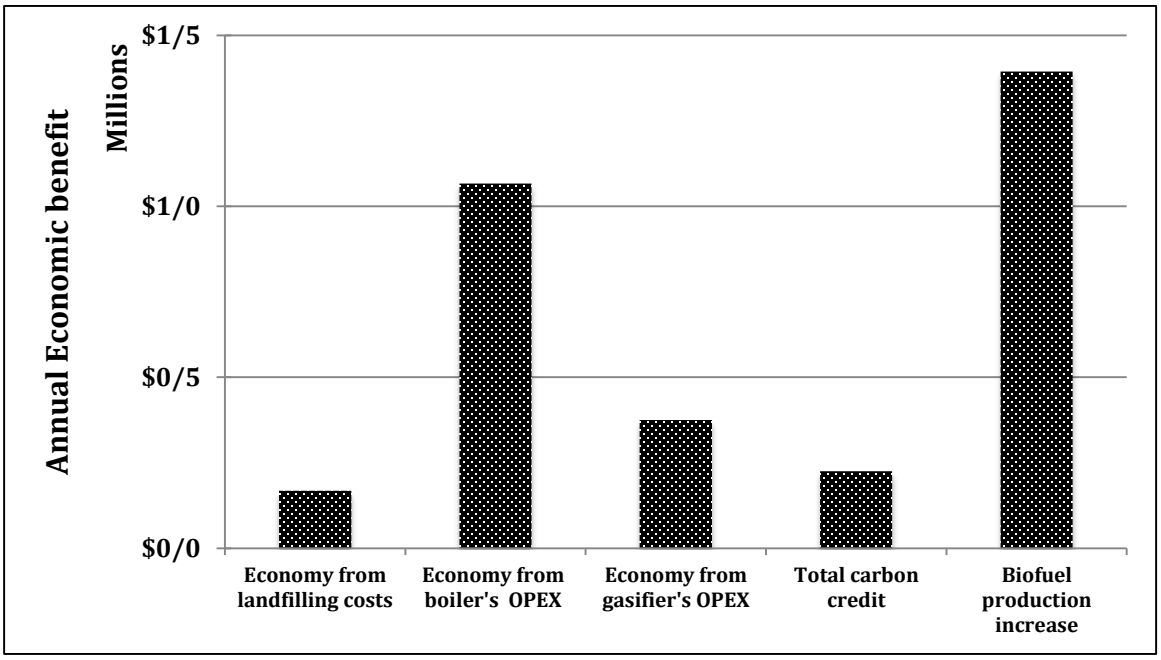




(b)

Figure 3.10. Market price of (a) diesel and (b) gasoline fuels in different regions in 2014 (source: US department of energy)

(a)



(b)

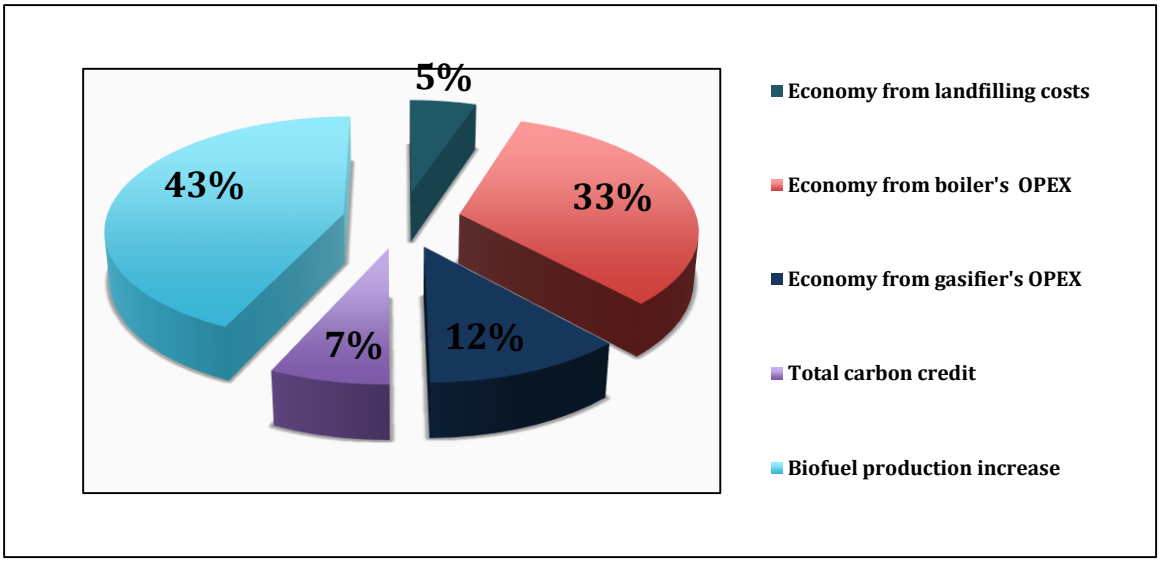


Figure 3.11. Benefits of continuous biodrying after integration to the base case mill (a) annual economic benefit (b) shares of the benefits

The program addresses the critical requirements for capital investment, which is non-repayable contribution to innovative and first-in-kind technologies. It covers up to 50% of the project's cost for either pilot or commercial scale technologies (*INVESTMENT IN FOREST INDUSTRY TRANSFORMATION*, 2014).

Industries generally target the internal rate of return of more than 20% to consider a project profitable and successful. However, in immature and high risk projects such as biorefinery technologies internal rate of return of greater than 30% should be targeted in order to minimize the risks and stay on the safe side (GILANI, 2014). For 500 dt/day biomass capacity without IFIT financial contributions, 20m-deep biodrying units are not among the interesting scenarios mainly due to the high fixed capital investment. Profitability assessment shows that bigger biodrying units and shorter residence times make biodrying process a viable option for the mill in conjunction with gasification process. In Table 3.13, the internal return rate of various biodrying scenarios for bigger units in conjunction with gasification have been listed. In 50m deep biodrying units, the internal rate of return without government contributions in ten and seven days residence time for the best scenario are respectively 3% and 9%, which have considerable difference from acceptable return rate, and in case of financial contribution up to 50%, they rise up to respectively 14% and 23%, which still have difference from targeted IRR.

However, satisfactory return rates are obtained where there would be financial contributions on the initial investments. In case of 25% contribution the acceptable return rates take place at 3 days residence time if carbon loss of biological aerobic activity inside the reactor does not exceed 5%. Government contribution up to 50% of the investment cost extends the acceptable return rate of biodrying technology to 4 days residence time and 10% carbon loss where airflow rate should not exceed 28 m^3/hr per cubic meter of biodrying reactor. In such scenarios IRR are varied between 30-55%. Ten biodrying conditions listed in Table 3.14 are considered as biodrying viable conditions in conjunction with gasification-based biorefinery of the base case mill.

Table 3.13. The internal rate of return of various biodrying scenarios

Biodrying Scenarios		IRR without government contribution	IRR with 25% government contribution	IRR with 50% government contribution
10 days Residence Time	5% carbon loss 50m deep units 20 m^3/hr airflow rate	3%	7%	14%
7 days Residence Time	5% carbon loss 50m deep units 20 m^3/hr airflow rate	9%	14%	23%
4 days Residence Time	5% carbon loss 50m deep units 20 m^3/hr airflow rate	17%	26%	42%
	5% carbon loss 50m deep units 28 m^3/hr airflow rate	19%	24%	39%
	10% carbon loss 50m deep units 20 m^3/hr airflow rate	14%	20%	32%
	10% carbon loss 50m deep units 28 m^3/hr airflow rate	12%	18%	30%
3 days Residence Time	5% carbon loss 50m deep units 20 m^3/hr airflow rate	24%	34%	55%
	5% carbon loss 50m deep units 28 m^3/hr airflow rate	23%	32%	51%
	10% carbon loss 50m deep units 20 m^3/hr airflow rate	19%	27%	41%
	10% carbon loss 50m deep units 28 m^3/hr airflow rate	17%	25%	39%

Table 3.14. Viable biodrying conditions for gasification-based biorefinery process in the base case mill

Condition	Final Biomass Dryness Level	Residence Time	Reactor Depth	Carbon Loss	Airflow Rate per m^3 of reactor	IRR
(1)	> 80%	3 Days	50 m	5%	20 m^3/hr	55%
(2)	> 80%	3 Days	50 m	5%	28 m^3/hr	51%
(3)	> 80%	4 Days	50 m	5%	20 m^3/hr	42%
(4)	> 80%	3 Days	50 m	10%	20 m^3/hr	41%
(5)	> 80%	4 Days	50 m	5%	28 m^3/hr	39%
(6)	> 80%	3 Days	50 m	10%	28 m^3/hr	39%
(7)	> 80%	3 Days	50 m	5%	20 m^3/hr	34%
(8)	> 80%	4 Days	50 m	5%	20 m^3/hr	32%
(9)	> 80%	3 Days	50 m	10%	28 m^3/hr	32%
(10)	> 80%	4 Days	50 m	10%	28 m^3/hr	30%

3.5.14. Techno-economic conclusion

The preliminary techno-economic analysis investigates the economic viability of continuous biodrying technology- developed at École polytechnique de Montréal (Canada)- implemented in gasification-based biorefinery process at pulp and paper mills. The study identified the conditions that biodrying can be employed economically in the mills instead of conventional drying technologies. By reviewing several gasification technologies in the literature it was concluded that the final dryness level of biomass is the most important parameter of biodrying, which must reach to higher than 80% before gasification process. Therefore, in this preliminary techno-economic study it has been assumed that biodrying can achieve such dryness level in all of the scenarios. Biomass capacity of 500 dt/day, bulk density of 300 kg/m^3, and different scenarios include 3, 4, 7, 10 days residence time in the reactor, 20m and 50m deep reactor designs, 5%, 10%, 20% biological carbon loss, 20 and 28 m^3/hr airflow rate per each cubic meter of biodryer were considered. Fixed capital investment and annual operating cost of different scenarios were estimated, potential benefits from implementing the biodrying system were highlighted, and economic performances of the scenarios were assessed. From techno-economic results it was concluded that the viable conditions take place where:

- Targeted dryness level is achieved within 4 days and less
- Carbon loss of aerobic biological activity is 10% and less
- Biodrying units have 50m depths

Airflow rate in the range of 20-28 m^3/hr per cubic meter of reactor only changes few percentages of internal rates of return and doesn't have significant impact on the viability of biodrying system. Since the fixed capital investment corresponds to residence time, higher time of retention imposes more initial cost. Among the scenarios, 7 and 10 days residence time make the biodrying system not a suitable option for gasification-based biorefinery process, where all the viable conditions take place in 3 and 4 days residence time. Fixed capital investment of 50m deep biodryer at 3 days retention time is competitive to superheat steam dryer that costs around M$ 5 for the same biomass capacity ("Project Independence Study: Liquid fuels from bimoass, feasibility study - Scope and estimates," 2010) but it is more expensive than rotary dryers, which costs around M$ 2.5 (Badger, 2002) for such capacity. On the other side, conventional dryers

bear high operating costs; superheat steam and rotary dryers require respectively 4 and 5 mega joule external energy per each kg of water evaporation (Fagernäs et al., 2010) that imposes costs to mills, whereas biodryer skips such cost. However, in the biodryer final dryness level at discharge is the most important parameter for its viability in conjunction with gasification and bound water removal is the significant challenge and major risk to reach such dryness level.

Chapter 4 : Experiments on biomass biodrying

4.1. Experiment targets

After assessing the economic viability of the continuous biodrying technology in the gasification-based biorefinery process, experiments are conducted to explore its technical feasibility for gasification application. From the literature review and preliminary techno-economic analysis two types of parameters are identified:

1) Parameters linked to the technical feasibility of study
2) Parameters linked to the economic viability

Moisture content (dryness level) is the single most important variable for evaluation of biodrying (Velis et al., 2009). Therefore, such variable along with the bed temperature are considered as important parameters for technical feasibility of biomass biodrying. Temperature increase is the indication of biological activity in the reactor that ultimately increases the dryness level to appropriate level required for gasification. Moisture content less than 20% is mandatory for gasification process of this study. If the biological activity happens and the required dryness level can be achieved, then biomass biodrying is technically feasible for gasification application. Residence time, biomass loss and airflow requirement affect the economic viability. However, the primary goal of the experiment is to activate the microorganisms and the secondary goal is to see if final dryness level of reaches the desired level appropriate for gasification. Thus, bed temperature and moisture content are closely monitored in the experiments.

4.2. Experiment

Experimental phase consists of: understanding how biodrying pilot set-up works, commissioning of the set-up, designing the experiment sets, material characterization, nutrient and moisture adjustment, conducting the experiments, Screening the bed temperature and moisture level, and finally analyzing and reporting the data.

4.2.1. Description of pilot-scale biodrying set-up

The set-up installed at École polytechnique de Montréal consists of two vertical pilot-scale stainless steel reactors with dimension of 2m × 1m × 0.4m (height, length, width) (Figure 4.1). Biomass is fed from the top at 1st compartment and moves downward by means of gravity force. Each column has been divided into four nominal compartments through which different aeration strategies can be applied. A series of perforated plates with uniform mesh have been installed on both sides of each compartment to uniformly distribute the air into the biomass matrix and avoid anaerobic conditions. Ultra high molecular weight (UHMW) polyurethane with 2.5cm thickness insulates interior wall of the reactors to minimize the friction and stickiness of biomass against the wall and facilitate its movement downward. Convective air is supplied to each compartment in cross flow pattern via a positive (2HP/600V/3P) and a negative (2HP/600V/3P) blowers; the positive induces ambient air into the reactor whereas the latter vacuums it from the reactor (Figure 4.2). The heat inside the reactor is generated as soon as biological activity takes place inside the reactor where bacteria decompose the biomass. Temperature rise in the reactor is the indication of such heat generation (see section 2.4.3) that is measured by sensors.

Figure 4.1. Pilot-scale biodrying machine installed at École polytechnique de Montréal

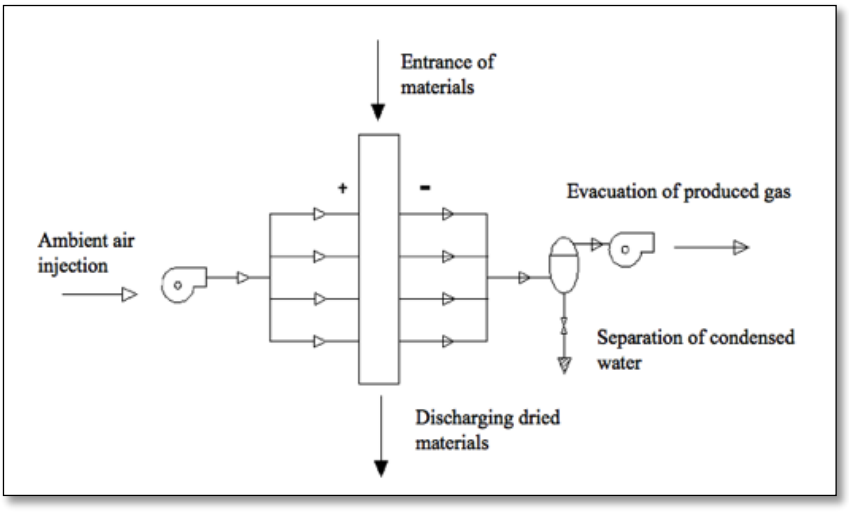


Figure 4.2. Positive and negative blowers of biodrying machine

One of the columns has fully been instrumented and controlled online. The other has limited instrumentation and principally designed to generate data for repeatability purposes. Online measurements of the equipment include internal bed temperatures, inlet/outlet air temperature, inlet/outlet air relative humidity, inlet/outlet CO_2 concentration, and airflow rates.

Air temperature and relative humidity are measured by six RH&T probes HMW60U/Y model of Vaisala, Helsinki, Finland (one installed at air inlet, four at each compartment's outlet stream, one is mobile for manual readings). CO_2 level is measured by a CO_2 analyzer Ultima™ gas monitor MSA Instrument Division, USA, attached to ABB sample gas unit SCC-E model. Airflow is measured by eight (four inlets/ four outlets) FOXBORO vortex flow meters, I/A series, Invensys™. All the process data are recorded by LabView 8.0.1 interface, National Instrument Inc., USA (Figure 4.3).

Two parallel 2hp mechanical screws uniformly pull out bio-dried biomass at the bottom of the reactor. Non-uniform discharge causes bridging problem in the reactor as well as non-uniformity in the dry solid content, therefore screws were designed in the way to minimize the risk of these problems. Several sampling ports have also been designed on the reactor's wall for taking samples for analysis. A platform and a ladder are also included to facilitate the loading of biomass.

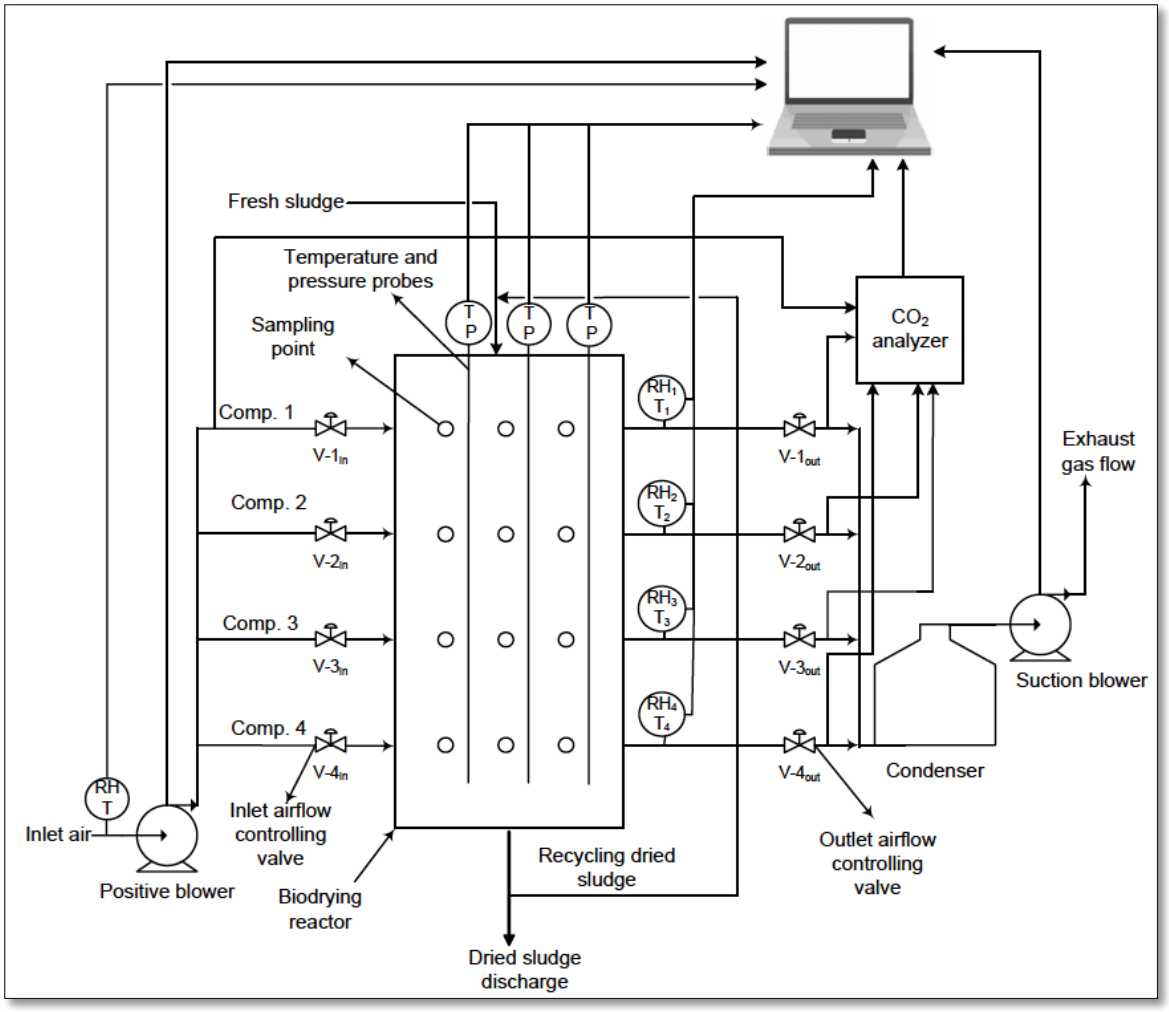


Figure 4.3. Instrument ad online control system of the pilot-scale biodrying reactor

4.2.2. Experiment series

In the previous study (biodrying of mixed sludge), outlet relative humidity was identified as the key variable and used for controlling the biodrying process. Two levels were then specified: high and low. 96% represented the higher level that has been reported to be suitable for falling rate period (see section 2.1.2.6) that enhances microbial activity, and 85% represented lower level that has been reported to be convenient for constant rate period correspond to unbound water removal (Shahram Navaee-Ardeh, 2010). Therefore, four outlet relative humidity (RH) profile strategies were tested in the reactor's compartments: 1) 85/85/85/85 strategy, 2) 96/96/96/96 strategy, 3) 96/96/85/85 strategy, 4) 85/85/96/96 strategy.

Blowing more air to remove unbound water at the top and less air to remove bound water at the bottom (4th case) resulted the best efficiency index among four cases (Shahram Navaee-Ardeh, 2010). Residence time impacts the drying performance and affects at the same time the economic viability. In the preliminary techno-economic analysis 3, 4, 7, 10 days residence time scenarios were assessed (see section 3.5.2). Recycle ratio creates uniform porosity in the biomass matrix and helps faster start-up of the biological activities, that ultimately helps decreasing the residence time. At 30% recycle ratio the populations of mesophilic and thermophilic microorganisms have been reported in the highest level (Shahram Navaee-Ardeh, 2006). (Kenneth Michael Frei, 2004) had also recommended this percentage. Therefore, 9 experiment runs were set to conduct the tests:

Table 4.1. Experiment runs

Run #	Residence time	Extra nutrient	Additional substrate	Process control	Airflow rate (m^3/hr)	Recycle ratio	Initial moisture
1	10 days	No	No	Outlet RH	32-80	0%	60-65%
2	10 days	No	Yes	Outlet RH	32-80	30%	60-65%
3	10 days	Yes	Yes	Outlet RH	32-80	0%	60-65%
4	10 days	Yes	Yes	Outlet RH	32-80	30%	60-65%
5	10 days	Yes	Yes	Airflow	8	30%	60-65%
6	10 days	Yes	Yes	Airflow	8	30%	60-65%
7	10 days	Yes	Yes	Airflow	8-28	30%	60-65%
8*	4 days	Yes	Yes	Airflow	8-28	30%	60-65%
9**	3 days	Yes	Yes	Airflow	8-28	30%	60-65%

* if successful biodrying is achieved and final dryness level reaches to the desire level in 10 days residence time

** if successful biodrying is achieved in 4 days residence time and final dryness level reaches to the desire level in 10 days residence time

In the laboratory, fresh biomass is completely mixed with a portion of discharged biomass in a barrel and conveyed to the first compartment of the biodrying reactor from the top. It is used as biomass inlet for the experiments in the case of 30% recycle ratio.

4.2.3. Material characterization

4.2.3.1. Solid phase (biomass) characterization

Solid content of the experiment consists of woody biomass and water. The biomass is wood

pellets of 20mm length (Figure 4.4-a). They have been bought from RENO Depot and transported to laboratory in 18 Kg packages. In the laboratory, they receive some water to reach to the designed initial moisture level. As soon as the pellets are soaked, they turn into sawdust shape with length of around 5mm (Figure 4.4-b).

(a)   (b)

Figure 4.4. Woody biomass used in the experiments (a) dry wood pellets (b) pellets after soaking

Biomass sample (200 grams) is sent to the certified laboratory of university of Montreal) for elemental analysis, from which carbon to nitrogen ratio (nutrient level) could be estimated in the experiment. Results of the analysis have been shown in Table 4.2.

Table 4.2. Elemental analysis of biomass used in the experiment

Elements	**Percentage**
Carbon (C)	49.07%
Hydrogen (H)	6.18%
Nitrogen (N)	0.02%
Oxygen (O)	44.73%

Moisture content of biomass is the quantity of water that exists in the biomass matrix. Since one of the goals of the experimental phase is to decrease the moisture to the appropriate level for gasification, this parameter was measured and monitored consistently during the experiments. To measure the moisture content three samples of biomass (40-50 gr each) were taken from different sampling ports of the compartments (see Figure 4.1) and oven dried at 105 °C for 24-30 hours. Moisture contents were then measured by the difference between wet and dry weights. Bulk density of the biomass was measured using a small vase. Known quantity of water was added to

the known weight of dry biomass in a way to reach the initial moisture content of the experiment. The mass of wet biomass is therefore known as well as the dimensions of the vase, so the bulk density was measured as the ratio of mass of the wet biomass to volume of the vase.

4.2.3.2. Gas phase (air) characterization

The blowers attached to the reactors supply the required air for biodrying. Laboratory conditions are not changed due to the regulations of the university; therefore ambient conditions in the experiments remain virtually limited, which does not represent real ambient conditions in the industry. Both the relative humidity and temperature of the ambient air have significant impact on the capacity of air for holding and removing moisture from biomass. Inlet and outlet relative humidity and temperature of each compartment were measured online through RH and temperature probes, and a thermometer was used for verifying the accuracy of the online measurements.

4.2.4. Nutrient level of biomass

Elemental Analysis Laboratory of the University of Montreal (UdeM) has reported the composition of wood pellets samples used in the pilot-scale biodrying reactor, as shown in Table 4.2. Therefore, C/N ratio of biomass that represents the nutrient level is estimated as 2500:1, which is much higher than the ideal range. The ratio less than 15 or more than 30 is out of the range, which is harmful for microbial activity (see section 2.4.3.4). The recommended range for biodrying has been reported as 24-29 by (Shahram Navaee-Ardeh, 2010). Therefore, fertilizer with NPK number of 28-4-8 (N%, P_2O_5%, K_2O%) was dissolved in water and mixed with biomass feed in the barrel, in order to adjust the nutrient level for biodrying.

4.2.5. Analysis of the results

The primary goal of the experiments was to activate the microorganisms and the secondary goal was to achieve the dryness level of 80% and more. Temperature increase in the reactor is the sign of microorganisms' activity, which is tied up to more intense mechanism for bringing bound water to the surface of the biomass particles. During the experiments, the moisture content (dryness level) of each compartment along with the moisture of inlet and discharge were

measured consistently by oven drying approach (see section 4.2.3.1). Results have been briefly listed in Table 4.3 and temperature profiles along the height of the reactor have been depicted briefly in Figure 4.5 and Figure 4.6 (for details see Appendix-B) along with the corresponding moisture levels. In these graphs Y-axis represent the height of the reactor where biomass moves downward during the retention time and X-axis shows the temperature in °C and moisture content in percent, respectively. Grey lines have separated each compartment of the reactor on the graphs. On the temperature figures red lines show the inlet air temperature to the reactor and black colors show temperature of the compartments. The air was ambient in the range of 14-30 °C depending on the laboratory conditions. In the first four experiments the reactor didn't heat up and temperature win all the compartments was always below the air temperature in the range of 14-23 °C. However, the convective air removed few percent of the biomass moisture (part of the unbound moisture). In the last three experiments temperature rose to the range of 36-38 °C, which showed the bacteria were activated. The details can be found in the table and on the graphs here and in the appendix B.

Table 4.3. Experiment results in terms of temperature and dryness level

	Ambient Temperature		Bed Temperature		Biomass Moisture level		Activation of microorganism	Desired dryness level
Run #	Min T	Max T	Min T	Max T	Inlet	Final		
1	25 °C	28 °C	15 °C	20 °C	61%	54%	No	No
2	25 °C	30 °C	17 °C	23 °C	66%	56%	No	No
3	18 °C	23 °C	14 °C	20 °C	68%	56%	No	No
4	17 °C	25 °C	14 °C	21 °C	67%	60%	No	No
5	15 °C	25 °C	15 °C	36 °C	60%	56%	Yes	No
6	18 °C	26 °C	22 °C	38 °C	60%	53%	Yes	No
7	14 °C	28 °C	19 °C	38 °C	68%	48%	Yes	No

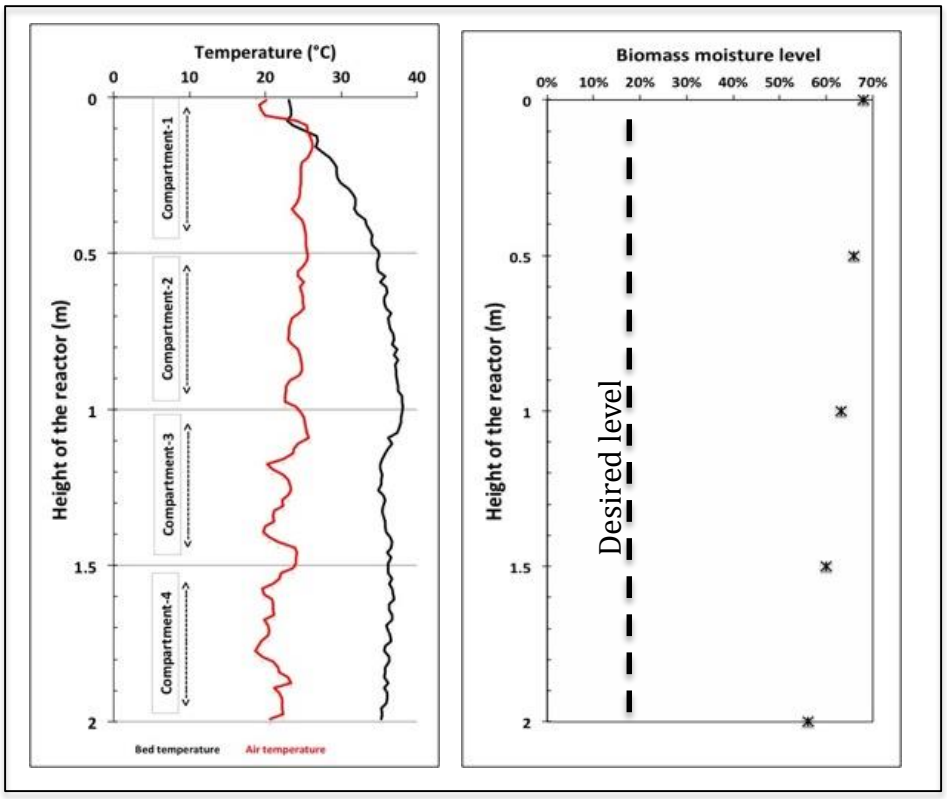


Figure 4.5. Temperature profile inside the biodrying reactor along the height and the corresponding biomass moisture level (Experiment # 6)

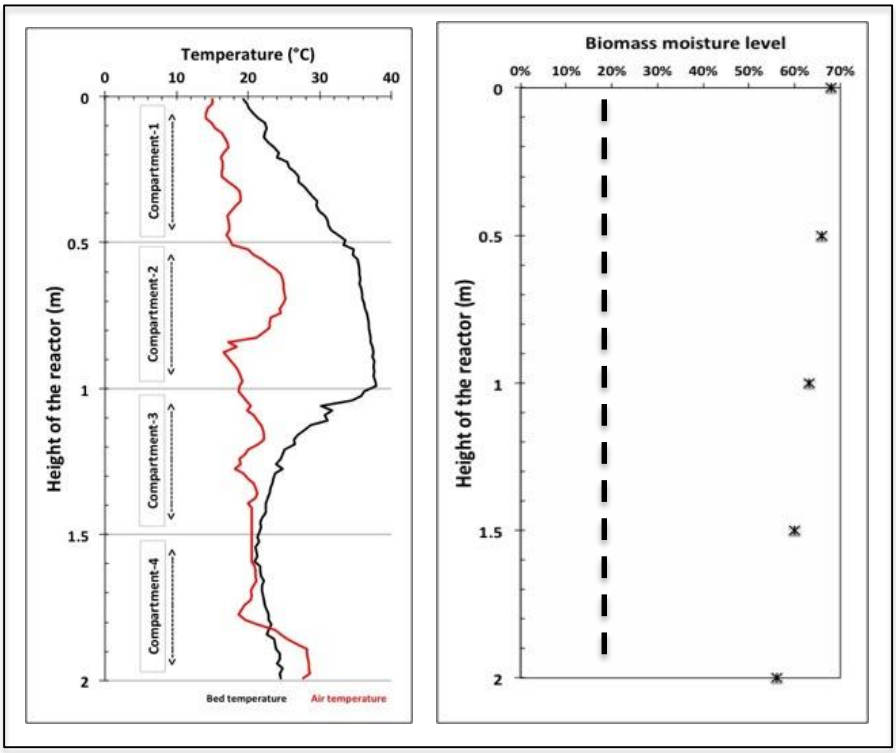


Figure 4.6. Temperature profile inside the biodrying reactor along the height and the corresponding biomass moisture level (Experiment # 7)

4.2.6. Experiment conclusion

Temperature rise inside the reactor's bed is the indication of biological activity of microorganisms and lets us make conclusion that biomass biodrying is technically feasible. Temperature around 38°C is the ideal range for activity and growth of mesophile microorganisms (Figure 2.8). In the last three experiments, the stable temperature around 36-38°C were observed that shows mesophilic microorganisms were activated. Final moisture content however, in none of the experiments reached to the proper level for gasification even by blowing more convective air (experiment # 7), mainly due to the low bed temperature, which was not enough to bring the bound water to the surface of biomass particles. From the experimental phase it is concluded that biomass biodrying by adding nutrient is technically feasible but it requires more studies and optimization for better performance. For successful biomass biodrying it is necessary to add enough concentration of nutrient to low nutrient biomass in order to supply sufficient food for bacterial activity. Besides, the airflow rate must be kept low enough (see Table 4.1) in order to not sweep away the heat from the reactor (temperature gradient to be developed) so that bacterial growth happens and goes on. For better biodrying performance it is essential to make more efforts to understand how to raise the temperature naturally in the reactor to the thermophilic and hyper-thermophilic range. This helps developing temperature gradient in the system and removing the water that is chemically bound into the biomass structures and ultimately helps lowering the final moisture content to the level appropriate for gasification. Further to raising the temperature it is also necessary to gain and incorporate the knowledge of keeping the thermophyl and hyper-thermophyl bacteria active as well as keeping temperature high during the retention time. Different thermochemical processes use different biomass types depending on which geographical region they have been established or what types of biomass residue is available in the mill or etc., so the successful biodrying of low nutrient biomass makes possible the drying of such biomass without consuming external energy. Biodrying of mixed sludge was proven feasible in the previous works where enough concentration of nutrients was inherently available, but the feasibility of biodrying using low nutrient biomass had not been proven. By this work it became clear that biodrying technology has great potential to be used for drying of all types of biomass including low nutrient biomass. The experiments of adding nutrient to biomass proved that biodrying of low nutrient biomass are technically feasible in an engineered process. However, biodrying is a complex process involved simultaneous heat, mass and momentum

transfers. Transport of the nutrient within the biomass occurs by liquid diffusion where water transports and supplies the dissolved nutrients for microbial growth in the biomass matrix. Then effective internal heat and mass transfers occur that accelerates internal moisture diffusion in the solid phase and helps bound moisture diffusing to the surface of particle for removal. Such transport phenomena mechanistic models combined with experimental data must be developed for process design or optimization of any biomass biodrying process.

Chapter 5 : Conclusions and recommendations

5.1. Contribution to the body of knowledge

One of the important challenges of gasification is feedstock quality especially in terms of moisture content. Combustion boilers can tolerate higher moisture contents in the cost of reduced energy efficiency whereas gasification process requires moisture level around 15% to reduce the tar content in the produced gas. The quantity of tar increases while biomass moisture level rises, so it is necessary to diminish the biomass moisture content to the appropriate and economic level, in the pre-treatment unit. Successful test results of the mixed sludge biodrying for boiler application (on the pilot scale biodryer), and the corresponding estimated economic benefits encouraged us to investigate the applicability of the continuous biodrying process as an alternative drying option for gasification process. Techno-economic analysis identified the conditions that biodrying process can be employed economically instead of conventional drying technologies. The most viable biodrying conditions are at residence time of four days and less, carbon loss of the biological activity 10% and less when biodrying unit design has 50m depths.

Availability of nutrient in the biomass matrix is one of the key factors for successful biodrying, and since biomass materials (except for example, activated and mixed sludge) inherently have low nutrient level, the feasibility of biomass biodrying was an important unknown in this work. For the initial observations prior to process optimization, biodrying of woody biomass was tested in the continuous biodrying reactor where nutrient was added to the biomass. Addition of nutrient adjusted the carbon to nitrogen ratio to those sufficient for aerobic biological activity. Temperature in the biodryer rose to the range of mesophilic bacterial activity, reaching a maximum of 38°C that showed biodrying of low-nutrient biomass is technically feasible. It is believed that the rate of moisture removal can be improved by activation of thermophilic and hyper-thermophilic microorganisms, which raise the temperature inside the reactor, therefore, it is recommended that further works be focused on the biology of these bacteria in addition to optimization of the process. In this work, due to safety reasons the biomass used for the experiments was not among those usually used in or recommended for the industry. Wood pellets in the experiments did not contain substrate therefore glucose substrate was added. Thus, it is likely that biodrying returns different results for such biomass types than the one tested in the reactor mainly because of C_5 and C_6 sugar naturally exist there. However, it is expected that

biodrying to show better performance at industrial process because the conveyed activated sludge as a source of nutrient contains hot acclimated microorganisms that boosts the performance of the biodryer.

5.2. Future works

- Consider combining biomass biodrying with superheated steam drying system in order to reach the target 80% dryness level with finely divided biomass; it would be essential to conduct energy integration studies with the gasifier and other site processes and facilities in order to maximize the value of lower grade steam from superheat steam dryer

- Testing a type of biomass that is used in the industry for gasification along with biological sludge as a source of nutrient

- Investigating the biology of biodrying process to find how to activate thermophile and hyper-thermophile microorganism in order to increase and keep the temperature close to vaporization temperature.

- Consider optimizing the biodrying process [recirculation acclimated biomass, addition of acclimated sludge and associated moisture, pre-treatment of biomass to maximize surface area while maintaining good pneumatic biodrying conditions, etc.] for short retention time under 3 days

- Testing other types of the woody biomass in the pilot reactor to validate the experimental results for other biomass types

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APPENDICES

Appendix A. Article 1:

Techno-Economic Analysis of Continuous Biodrying Process in Conjunction with Gasification process at Pulp and Paper Mills

Arash Hamidian, Zahra Sarshar, and Paul R. Stuart*

Department Of Chemical Engineering, École polytechnique de Montréal, QC, Canada, H3C 3A7

Abstract:
In the biorefinery context, thermochemical processes such as gasification, pyrolysis and combustion that convert biomass to bioenergy, biofuel and biochemical have attracted significant attention in recent years. Thermochemical processes generally consist of three main steps: pre-treatment, thermochemical treatment, post-treatment. In these developing processes drying and feeding of biomass feedstock remain a significant and costly challenge. The moisture content of biomass feedstock must be decreased to an economic level at pre-treatment step otherwise it has a detrimental effect on the process efficiency and quality of products. In this work, we focus on the drying of biomass feedstock using novel but practical technology, called biodrying. Biodrying is a green technology that offers an opportunity for biomass drying without the need for using an external heat source or fossil fuels, since drying energy is generated through exothermic microbial activity in the biomass that enhances the drying rate. In this paper we focus on techno-economic assessment of continuous biodrying technology integrated to gasification-based biorefinery process and investigate the conditions that make such novel technology viable in conjunction with gasification process. Fixed capital investment and operating cost of different biodrying scenarios are estimated and potential benefits from integration of the continuous biodrying system in gasification process implemented in pulp and paper mill are highlighted, and ultimately economic performances of the scenarios are assessed. Furthermore, the viable biodrying conditions are specified and the major viability risk is addressed.

Keywords: biodrying, biological drying, biomass biodrying, gasification, biorefinery, economic assessment, techno-economic analysis

1- Introduction

One of the significant challenges of biomass gasification compared to combustion is the limitation in quality of feedstock particularly in terms of moisture content [1, 2], which plays an important role in gasification performance. Combustion boilers can tolerate higher moisture contents for the cost of reduced energy efficiency [3] whereas gasification process requires low moisture levels. Several reports have highlighted the moisture content as a typical problem while gasifying biomass [4, 5]. Fresh biomass has in average 30-60% moisture content, which is not appropriate for gasification. Moisture content in biomass has a great impact on the performance of gasification process and mainly reduces overall reaction rates as a result of temperature drop. It affects drying and the subsequent de-volatilization and gasification stages. Evolution of volatile gas in de-volatilization stage is basically a two-step process: first biomass yields tar, primary volatile gases (CO, H_2, CH_4, etc.) and residual char in the pyrolysis zone, and in the second step tar is cracked and transformed to secondary volatile gases ($C_nH_x \leftrightarrow nC + (x/2)H_2$ & $C_nH_x + mH_2O \leftrightarrow nCO + (m + x/2)H_2$) [1, 6, 7]. Besides, hydrogen and carbon monoxide are produced through some gasification reactions such as Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$), steam-carbon reaction ($C + H_2O \leftrightarrow CO + H_2$), and methane

reforming reaction ($CH_4 + H_2O \leftrightarrow 3H_2 + CO$), which are highly endothermic. Higher moisture content in biomass consumes more heat for evaporation and drops the gas and particle temperatures [1, 4], which lowers the de-volatilization rate and shifts the equilibrium of the endothermic gasification reactions toward the formation of carbon dioxide and water. Therefore, moisture mainly targets the gasification and second de-volatilization steps resulting tar content increase [6, 7], gas yield decrease, gas composition change [6, 8] and hence the efficiency of gasifier, apart from operational problems due to tar, is ultimately affected [9]. Kaewluam et. al. (2010) have gasified rubber woodchips of different moisture contents in a small fluidized bed gasifier and reported significant operational difficulties at moisture level higher than 30% [9].

Therefore, it is necessary to treat biomass moisture and decrease it to an appropriate and economic level in pre-treatment units. Several reports have stated 15-20% biomass moisture content as a proper level for gasification [3, 10]. Solutions for high moisture biomass are either employing natural drying technic or using conventional drying technologies. For commercial scale plants the natural drying is not practical because it requires extensive lands and also the sunlight is limited in many regions during the year. On the other side, the conventional drying technologies bear high operating cost if there would be no or expensive heating source in the plant [9], therefore, an innovative method is needed to dry biomass economically. Biodrying (biological drying) is an alternative process to conventional thermal drying that employs heat of biological reactions in addition to forced aeration, to reduce the moisture level of biomass. It is believed that employing biodrying for biomass pre-treatment in gasification units returns several economic and environmental advantages and has created encouragement for this study.

The term "biodrying" had primarily been used by Jewell et. al. (1984) while reporting operating parameters of daily manure drying [11]. Three main current applications of biodrying include: Municipal Solid Waste (MSW) treatment, grape waste treatment in wine industry, and moisture removal of mixed sludge biomass at pulp and paper mills [12-14]. The first one has been practiced since more than a decade ago in Europe as a part of MBT (Mechanical-Biological Treatment) technologies with 20 commercial references [15], whereas the two latters are potential applications still under development [16, 17].

In MSW treatment plants, waste stream is transformed to SRF (Solid Recovered Fuel) for waste-to-energy options instead of landfilling. In such units, the entire MSW stream enters to biological process where biodrying degrades a part of the biodegradable organic fraction of the waste and generates heat to evaporate moisture content, which results high heating value SRF comparable to brown coal, when fine fraction such as ash, glasses and stones are removed [18]. Some commercial biodrying technology providers for MBT application are Eco-deco, Entsorga, Herhof, Nehlsen, Wehrle Werk [15].

Valorization of grape waste through energy recovery is an option for wine industry to make economic and environmental benefits. The industry consumes 1.3 kg grape to produce a liter of wine where 20% are wasted after fermentation and distillation. Therefore, application of biodrying process for evaporation of water content and transforming the grape waste to SRF of different quality suitable for energy recovery has grabbed the attentions [13, 17].

Development of biodrying technology for pulp & paper industry was started at École Polytechnique de Montréal in 2004 and widely studied since then. It had primarily been reported as the most cost effective option among different emerging sludge management

options at pulp & paper mills for increasing the dryness level of sludge for combustion [19]. To address this issue, batch biodrying system was developed at École Polytechnique in 2004 whose goal was to increase the dryness level of mixed sludge for efficient combustion in boilers [14]. Successful test results and annual $2 million operating cost saving estimation were the driving forces to develop continuous biodrying technology. Improved controllability and potentials of establishment in crowded pulp and paper mill sites were also identified as advantages of continuous technology over batch system [16]. In 2010, Navaee-Ardeh et. al. developed the mathematical model of continuous system and designed vertical pilot scale reactor in which mixed sludge was dried to 55% dryness, the appropriate level for efficient combustion in boiler [20].

The previous successful works encouraged us to continue the investigation of applying the continuous biodrying technology for other types of biomass than mixed sludge used as a feedstock in a biorefinery thermochemical process such as gasification where dewatering is an important pre-treatment step to achieve high quality syngas. This study consists of economic viability assessment of the continuous biodrying technology for biomass used in gasification process, followed by technical feasibility verification by experiments in a pilot reactor. One of the key factors for a successful biodrying is the availability of sufficient nutrient in biomass, which is essential for biological activity in the reactor (section 2.2.1). Various types of lignocellulose biomass used in the gasification processes naturally contain low nutrient level. Therefore conveying sludge from wastewater treatment units of pulp and paper mills, which is rich in nutrient can help biodrying to be successful and at the same time address landfilling management problem in the mill.
This paper presents results of the first part, techno-economic analysis, where economic performance of the continuous biodrying process implemented in gasification process integrated in pulp and paper mill has been assessed. Investment and operating costs were estimated, potential revenue sources were identified and economic performance of several scenarios along with conditions under which continuous biodrying can economically perform were investigated.

It is believed that under certain conditions continuous biodrying process is an economically attractive option for gasification-based biorefinery process integrated in pulp and paper mills. Preliminary techno-economic analysis principally aims to assess economic viability of the continuous biodrying process before experimental phase of the project. This assessment also allows us to identify the influential parameters and incorporate with experiment targets. Therefore, general objective of this study is to investigate the performance of continuous biodrying system that makes it economically a viable technology in conjunction with gasification (for biomass application), which reflects the winning conditions when implemented at retrofit with pulp and paper mills.

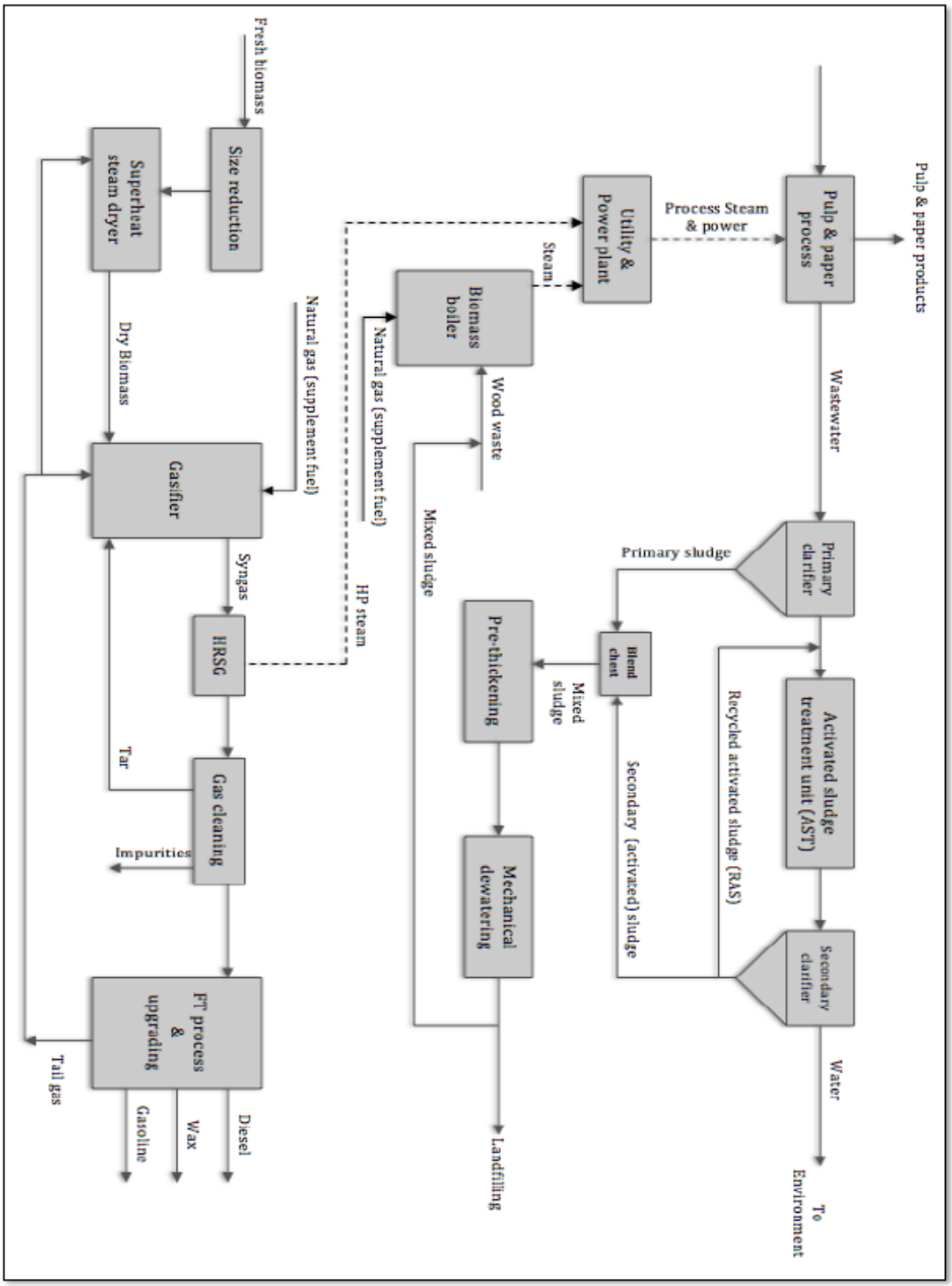
2- Materials and Methods

Common assumptions applied in techno-economic assessment of this work includes:

- All the costs indexed to 2014 dollars
- Project is financed by 100% equity in all the scenarios

To address the objective of this paper the following methodology was developed: a base case mill was defined and battery limit of the study was identified, several biodrying scenarios in terms of process, design and operating parameters were defined, mass and energy balances were performed, a reliable approach for cost assessment (fixed capital investment and operating cost) of biodrying system was found in the literature and introduced, relevant capital and operating cost of the scenarios were estimated, potential economic benefits of implementation of biodrying system were identified, costs and benefits were combined into economic return

Figure 1. Schematic of base case mill process before implementing biodrying system



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criteria, and finally acceptable economic performance for biodrying implementation was identified and the conditions under which it is achieved were determined.

2.1. Description of the base case mill

It is possible to integrate synfuel production process to existing pulp and paper mills and it is very common to foresee such integration [2]. For this techno-economic study, as illustrated in Figure 1, an existing pulp and paper mill was considered in which a gasification process followed by Fischer-Tropsch (F-T) process has already been integrated in order to produce F-T liquids. The pulp and paper process of the mill generates 60 m^3 wastewater per ton of paper, which is treated in wastewater treatment unit before releasing to environment. It is first treated in primary treatment unit where 70 odt/d primary sludge with 97% moisture content is generated, then treated in activated sludge basin to reduce the organic content resulting the generation of 30 odt/d secondary (activated) sludge with 97% moisture. Sludge from first and second treatment steps are mixed, the water content is reduced to 74% by mechanical dewatering, and 16% of this stream is then sent to landfill area whereas 84% is mixed with 300 t/d wood-waste of 50% moisture content to be disposed in power boiler for energy recovery. Power boiler also receives 22,000 Nm^3/d natural gas with composition mentioned in Table 1 as a supplement fuel to keep the efficiency of boiler high.

Table 1
Composition of natural gas consumed in the mill

Components	Composition (V%)
CH_4	89 %
C_2H_6	5.2 %
C_3H_8	1.9 %
C_4H_{10}	0.7 %
C_5H_{12}	0.4 %
C_6^+	0.02 %
N_2	2.7 %
Helium	0.02 %
Heating value	45 MJ/Kg

In the gasification process, 500 odt/d biomass with characteristics described in Table 2 enters the pre-treatment unit, size is reduced to less than 6 mm by disc shredders and then enters to superheat steam dryer that consumes 1,000 GJ/day tail gas of F-T process to dry biomass to 15% moisture content. Then, it enters to fluidized bed gasifier where 55,000 st.m^3/hr syngas composed of 21% CO, 40.6% H_2, 24.3% CO_2, 10% CH_4, 1.8% N_2, 1.3% C_2H_4, 0.7% C_2H_6 with calorific value of 12.5 MJ/st.m^3, and about 4 t/d tar are produced. Endothermic heat of steam reforming reactions is supplied through four heaters fully submerged in the bed that receive 1,500 GJ/day tail gas of F-T process and 250 GJ/day natural gas as external combustible fuels.

Table 2.
Biomass characteristics used in the gasification process

Biomass type:	Bark & wood waste
Moisture content:	50%
Bulk density:	300 Kg/m^3
Elemental analysis:	
C	49%
H	5.7%
O	40%
S	0.03%
N	0.01%
Inert and ash	5%

Tar and impurities are removed from raw gas and cleaned syngas is fed into the FT process where 1.8 m^3/hr (10,500 gal/d) wax, 2 m^3/hr (11,500 gal/d) diesel, 0.25 m^3/hr (1,300 gal/d) gasoline, and 500 ton per day unreacted (tail) gas with estimated energy flow of 2,500 GJ/day are produced.

2.2. Biodrying process, scenarios and implementation to gasification-based biorefinery process of the base case mill

2.2.1. Continuous biodrying process

The advantage of biodrying process compared to conventional drying technologies is to be a self-heating process mainly relied on the heat naturally generated by metabolic activity of

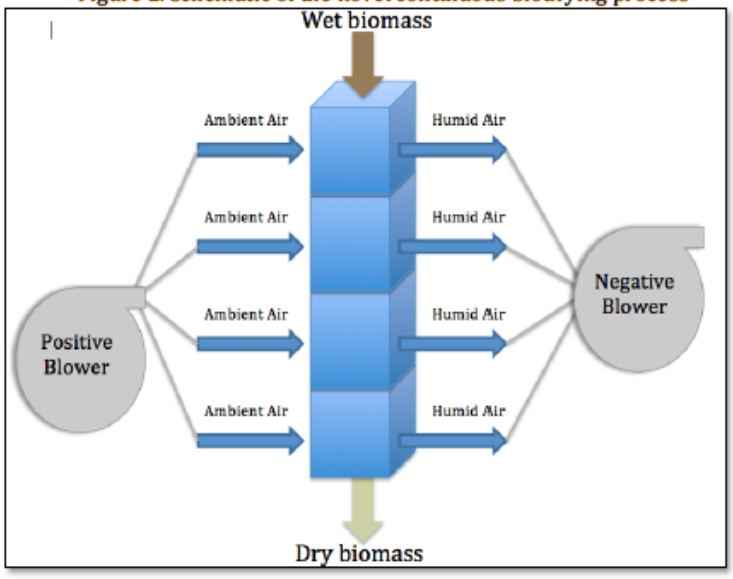
microorganisms through aerobic biodegradation of biomass substrate [16]. Different types of moisture that exist in biomass consist of unbound and bound water, which must be removed through the biodrying system. Each type requires different removal mechanism. Unbound water is the one that sticks to the surface of biomass particles and can be removed more easily whereas bound water is embedded into the particles' structure and needs more intense mechanism for removal. In biodrying physical and biochemical reactions are responsible for drying. The combination of forced convection and aerobic degradation are employed in the reactor where the first is responsible for physical reaction removing the unbound water whereas the latter represents biochemical reaction treating the bound water [21].

In the continuous biodrying reactor biomass is fed from the top and its dryness level increases while moving downward by means of gravity and finally discharged from the bottom. Drying phenomenon takes place in the width and height directions in the reactor where air is blown and biomass moves, as illustrated in Figure 2. Blowers supply necessary air for forced convection as well as for aerobic microbial activity.

In addition to forced aeration, metabolic activity of mesophilic and thermophilic microorganisms that exists in the biomass matrix helps reaching the desired drying temperature, which consequently boosts the drying rate. These bacteria catabolize biomass substrate to grow during biodegradation cycles [21] and ultimately enhance the drying rate and reduce the moisture as well as volatile matter of biomass. Microorganisms require enough oxygen (air), water and key nutrients as nitrogen (N), phosphorus (P) and sulfur (S) to satisfy their needs for metabolic activity and cell growth. Since moisture removal in the biodrying system is independent from fossil or external heating sources, the technology is addressed as green, energy efficient and sustainable.

By implementing biodrying process to the base case mill, secondary sludge of wastewater treatment facility is sent to biodryer to supply and guarantee enough nutrients for microbial activity inside the reactor.

Figure 2. Schematic of the novel continuous biodrying process



2.2.2. Biodrying scenarios for economic analysis

To perform economic analysis of biodrying process, influential parameters on the initial investment and annual operating costs were firstly identified. Capacity and bulk density of biomass feedstock impact the number of biodrying units affecting ultimately the fixed capital investment. The Ambient air temperature, blowers' efficiency and airflow requirement impact electricity consumption of blowers, and biological carbon loss imposes more biomass cost to the system and all of these influence the operating costs (section 2.2.4.).

Volume of reactor and biomass residence time impact both investment and operating costs of each reactor. A bigger reactor in terms of volume needs more airflow rate for biological activity and influences the electricity consumption. Longer residence time requires higher reactors to dry the biomass to the targeted level, which affects the fixed capital investment of biodrying process, and since it directly impacts reactor's volume the operating cost is affected as well.

Drying of biomass takes place in the height and width directions of biodryer and must be designed based on the operating conditions, but no drying happens along the depth, therefore this parameter represents the volume of reactor in the scenarios. Different biodrying scenarios in terms of influential parameters on the costs have been shown in Table 3.

Table 3.
Biodrying scenarios for economic analysis

Residence time:	3, 4, 7, 10 days
Reactor's depth:	20m, 50m
Carbon loss:	5%, 10%, 20% Of biomass inlet
Required airflow rate:	20, 28 $m^3/hr/m^3$ reactor

2.2.3. Fixed capital investment of biodrying system

Reliable estimate for capital investment (as well as operating costs) of biodrying system is essential for either techno-economic evaluation or equipment selection when comparing different options. Information regarding the equipment and process costs is usually confidential in the industry and it would be difficult to find a precise costing in the open literatures. It is therefore essential to use shortcut methods to quicken the estimates on fixed capital investment (FCI) and operating costs. Cost estimation of biodrying system follows the well-known method widely used in the process industries. It is applicable for rough estimation of biodrying or any other drying systems. Steps of preliminary estimation are schematically shown in Figure 3. When the size of dryer is known, purchased equipment cost of biodrying system are estimated, the installed cost, other fixed costs, and ultimately fixed capital investment are predicted using the factor method.

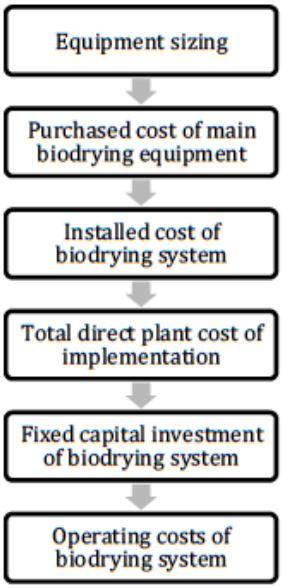


Figure 3. Cost estimation approach for continuous biodrying system

A biodrying reactor itself is just one component of the drying system therefore fixed capital investment and operating cost must be estimated for the whole system that is supposed to be implemented in the plant. Purchased cost estimation using data of technical literatures is one of the most common technics. Such data are mostly related to technical and economic conditions of the past that is likely to be very different from the actual conditions. Capacity and inflation rates are the ones being usually different in various cases. Therefore, former cost should be first updated to actual cost, and then scaled-up or down to the desired capacity [22].

2.2.3.1. Updating the costs

Due to inflation and inevitable fluctuations in the economy, costs and equipment prices are always subjected to change. Methods called Chemical Engineering Plant Cost Index (known as CE index) and Marshal & Swift All-industry Equipment Cost Index (previously known as Marshal and Steven cost index) are two most commonly used methods to cover inflations and updating the costs. However, the latter (M&S) has been recommended for updating high-level process equipment.

Table 4.
Marshall & Swift all-industry equipment cost index (1989-2004) [22]

Year	Index
1989	895.1
1990	915.1
1991	930.6
1992	943.1
1993	964.2
1994	993.4
1995	1027.5
1996	1039.2
1997	1056.8
1998	1061.9
1999	1068.3
2000	1089
2001	1093.9
2002	1104.2
2003	1123.6
2004	1178.5

Equation (1) is the formula widely accepted for equipment cost updating using M&S cost index and Table4 shows indices from 1989 to 2004 [22, 23]. The index of 2014 for biodrying cost estimations was estimated by extrapolation of these data.

$$Updated\ cost = Original\ cost \times \left(\frac{M\&S\ index\ at\ updated\ time}{M\&S\ index\ at\ the\ time\ of\ original\ cost}\right) \quad (1)$$

2.2.3.2. Scaling-up/down the costs to the desired capacity

For biodrying system, the cost of the same dryer type with different capacity can roughly be predicted by equation (2) [22, 24], which is an empirical formula.

$$Predicted\ cost = Original\ cost \times\times \left(\frac{Desired\ capacity}{Original\ capacity}\right)^{n} \quad (2)$$

Desired capacity is the capacity where cost estimation is supposed to be made, and original capacity is the capacity of the same biodryer where the cost is known. Exponent "n" has different values that are available in the references. Table 5 shows some examples for different dryers. If the value could not be found in any literature sources, then n=0.6 can be taken for very rough estimation [22], the one that has been considered for scales-up of biodrying system.

Table 5.
Exponent value for scaling-up/down the capacity[22]

Equipment	Capacity range	Exponent
Pan dryer	1-19 m²	0.50
Vacuum-shelf dryer	1.4-92 m²	0.54
Tunnel dryer	2-10 m²	0.50
Roto-Louvre rotary dryer	4-93 m²	0.62

2.2.3.3. Installed cost (IC), total plant's direct cost (TDC) and fixed capital investment (FCI) of biodrying process

Installed cost of biodrying system consists of the cost of purchased drying system, dispatching them to plant, assembly and installation, piping, wiring, instrumentation and control systems. Such costs can be estimated based on the vendors' data, previous known costs, or factor method. The latter has been applied in this paper.

There are additional charges to establish the biodrying process in a plant such as structures on which biodrying system is installed, site development, utility supply, and other direct expenses. Therefore, total direct plant cost is higher than installed cost. Contractor's fee, insurance, customs, taxes, land, procurement, supervisory, administration, contingencies, and other owner expenses related to the plant are added to TDC to estimate the fixed capital investment required for biodrying system.

Table 6 shows the factors considered for FCI estimation of biodrying system.

2.2.4. Operating costs of biodrying system

The last step in cost estimation of any drying process is operating cost estimations. Maintenance cost, lost or degraded raw materials, labor and utilities are costing elements of any drying systems as well as biodrying.

2.2.4.1. Maintenance

Maintenance cost is estimated by factor method. For complex conventional drying systems that contain explosive or toxic raw materials with several rotating and vibrating items, 10% of fixed capital investment (FCI) has been recommended whereas for simple conventional systems 5% would be acceptable [22]. For biodrying system of this study 3% of FCI has been considered since the system neither has many vibrating or rotating parts nor toxic or corrosive materials inside.

Table 6.
Factors considered for fixed capital investment (FCI) estimation of biodrying system

Category	Cost description	Cost factor	Reference
Purchased Cost (PC)	Purchased cost of biodrying reactors	Estimation by data of literature (section 2.2.3)	[25]
	Purchased cost of blowers	Estimation by data of literature (section 2.2.3)	[26]
Installed Cost (IC)	Assembly and installation, piping, wiring, instrumentation and control systems	25% of PC	[22]
	Freight	7% of PC	
Total Direct Plant Cost (TDC)	Structures on which biodrying system should be installed	15% of IC	
	Site development, utility supply, other direct expenses	20% of IC	
Fixed Capital Investment (FCI)	Contractor's fee	10% of TDC	
	Insurance, customs, taxes, land, other owner costs	7% of TDC	
	Procurement, supervisory, administration	5% of TDC	
	Contingencies	10% of TDC	

2.2.4.2. Lost or degraded raw materials

In conventional drying systems a small portion of raw materials is lost due to the heat delivered to dry biomass. In such systems, thermal destruction starts at about 150°C where hemicelluloses are destroyed and loss is accelerated rapidly when temperature increases more [2]. In the biodrying process there is not such temperature rise but a portion of biomass is lost due to degradation of organic fraction by bacteria (section 2.2.1). These losses should be compensated by auxiliary raw materials, which add up the annual operating costs.

2.2.4.3. Labor cost

Drying systems requires some personnel to handle the process. Unit cost of labor should be in compliance with local economy and must include insurance, taxes, and social charges. Labor cost of drying systems depends on the mode of process. In batch systems cost depends on the quantity of handled materials, type of equipment, schedule of plant's operation and can be roughly estimated as 2 man-hour/(m^3 of dried material)+1/3 man/dryer/shift. In continuous drying systems labor activities are restricted to supervision of control systems, feeding and discharge systems, which lowers labor cost compared to batch mode [22]. Operator requirements per unit per shift for different types of process equipment can be found in Table 7 [27].

Table 7.
Operator requirements of process equipment [27]

Equipment Type	Operator requirement /unit/shift
Blowers and compressor	0.1-0.2
Gas-solid contacting equipment [a]	0.1-0.3

[a] Coolers, dryers, fluidized beds, roasters

Continuous biodrying system comprises drying columns and blowers, therefore it is estimated that the process would require one fifth (0.2) of the attention of an operator to control the systems and handle the process. Thus, 1/5 man/biodrying unit/ shift can be estimated for labor cost of biodrying process.

2.2.4.4. Utility cost

Typical utilities generally include electricity, process steam, compressed air, cooling water, demineralized (boiler feed) water and etc. Among them, biodrying system implemented to gasification process requires only electricity and air for respectively blowers and instruments. Positive and negative blowers are the electricity consumers that supply air for aerobic activity. Power requirement of blowers is estimated from equation (4) with assuming isothermal air compression [28]:

$$Power\ (kW) = \frac{1.97 \times T_a \times Q_s}{\eta} \ln\left(\frac{P_b}{P_a}\right) \quad (4)$$

Where T_a is ambient temperature in Kelvin, Q_s is airflow requirements in cubic meter per second at standard condition, η is blower efficiency, P_a and P_b are blower's inlet and discharge pressures. By neglecting the cost of instrument air compared to electricity, the operating cost of biodrying system is identified. For this techno-economic study it is assumed ambient temperature as 25 °C, blowers' efficiencies as 90%, atmospheric inlet pressure and discharge pressure as 5% increase of the inlet pressure.

2.2.5. Economic performance

The most common mathematical methods for profitability evaluation are Return On Investment (ROI), Discounted Cash Flow (DCF), Net Present Value (NPV), and Payback Period (PBP). None of the methods are marked as the best and an engineer should be able to choose the best according to particular situation of project. DCF method is based on the amount of investment that is not returned at the end of each year during the estimated life of a project.

It considers the time value of money and requires trial-and-error procedure for obtaining the internal rate of return (IRR) that discounts the annual cash flow to zero present value. Such IRR is the normal interest or payoff of investment and often called profit of the project. In this paper profitability of implementing biodrying process to existing mill is under investigation so it is crucial to estimate the profit of such implementation to the mill where time value of money is taken into account. Therefore, IRR was selected as economic performance indicator, which is expressed in percentage[23].

2.2.6. Governmental contributions to innovative biorefinery technologies

Investment in Forest Industry Transformation (IFIT) program is governmental program created to accelerate the establishment of new technologies in the Canadian forest industry. The program aims to support the forest sector to become environmentally sustainable and economically more competitive. IFIT addresses critical requirements for capital investment and it is non-repayable governmental contribution to innovative and first-in-kind technologies that covers up to 50% of the project's cost for either pilot or commercial scale technologies[29].

2.2.7. Implementation of biodrying process to base case mill; mass and energy variations

Integration of biodrying process to the base case imposes some changes in mass and energy flow of certain streams inside the battery limit of the study. Transferring secondary sludge as a source of nutrient for microorganisms activity decreases the quantity of sludge sent to landfill area. Secondary sludge is a type of carbonaceous material that could augment the quantity of raw syngas production in the gasifier when dried, and ultimately increases the quantity of biofuel production in F-T process. Biodrying is a self-heating process and doesn't need external heating sources, therefore tail gas spent for the superheat steam dryer at base case is consumed elsewhere and could be replaced for natural gas used in power boiler and gasifier. Since tail gas is produced from renewable source, its combustion counted as zero-CO_2 emission to environment, thus replacing natural gas with tail gas mitigates CO_2 generation from fossil sources and reduces relevant CO_2 costs of the mill. All these changes correspond to some economic benefits for the mill. Table 8 shows estimations of mass and energy flow inside the battery limit before and after implementing biodrying process.

Table 8.
Mass and energy flows before and after implementing continuous biodrying process

	Base Case	After implementation of biodrying process	Increase/ Decrease	Remarks
Sludge to landfill odt/d *	16	0	-16	-
Natural gas (power boiler) Nm^3/d **	22,000	0	- 22,000	Saving by replacing FT tail gas
Natural gas (gasifier) Nm^3/d **	7,700	0	-7,700	Saving by replacing FT tail gas
CO_2 emissions (t/day)	64	0	- 64	FT tail gas comes from renewable sources
Biofuel production GPD ***	23,000	24,500	+1500	Wax, diesel, gasoline from F-T process

* odt/d: oven dry ton per day
** Nm^3/d: Normal cubic meter per day
*** GPD: gallon per day

3. Results and discussions

3.1. Costs and economic benefits of biodrying implementation

Different process, design and operating parameters reflect different total investment costs. Although a bigger reactor in terms of volume increases the cost of a single biodrying unit but at the same time it decreases the number of required parallel units in a constant capacity, compared to smaller reactors. Longer residence time needs higher reactors in order to satisfy necessary time of continuous movement and drying, which influence the total investment costs. Total number of required units in different scenarios has been shown in Table 9 and relevant fixed capital investment estimations have been depicted in Figure 4.

Table 9. Number of required biodrying units for 500 odt/d Biomass Capacity

Depth of the reactor	Units
20 m	17
50 m	7

Annual operating cost estimation of different biodrying scenarios have been shown in Figure 5 in which biomass and labor costs were assumed as $25 per green ton and $20/hour, respectively. Longer residence time requires more air during the drying period, which increases the electricity consumptions.

If continuous biodrying process is successfully implemented to gasification process in the mill and dries biomass to less than 20% moisture content (appropriate level for gasification process) by employing the combination of forced aeration and biological h eat, mass and energy flow of certain streams inside the battery limit will be changed (describes in section 2.2.7), which correspond to some economic benefits for the mill: 1) cost saving of sludge landfilling, 2) natural gas saving in power boiler, 3) natural gas saving in the gasifier, 4) CO_2 cost mitigation, and 5) revenue rise due to increase in biofuel production. Figure 6 shows the estimates of benefits in case of successful implementation.

CO_2 cost for mills has been reported as $10 per each ton of carbon dioxide [19], cost of natural gas was assumed $4/GJ (EIA website) and landfilling in average costs $30 per dry ton of sludge for mills [19]. Crude wax was assumed $3 per gallon. Market prices of diesel and gasoline at east coast region in 2014 have been reported as $3.6-$4.2 and $3.2-$3.7 per gallon respectively[30], where 13% tax (for both products) with marketing and distribution costs of 17% for diesel and 10% for gasoline were included [31], thus, average sales price of $2.73 and $2.70 per gallon for diesel and gasoline, respectively were assumed as mill's revenue.

Figure 4. Fixed capital investment of biodrying units for 500 odt/d biomass capacity

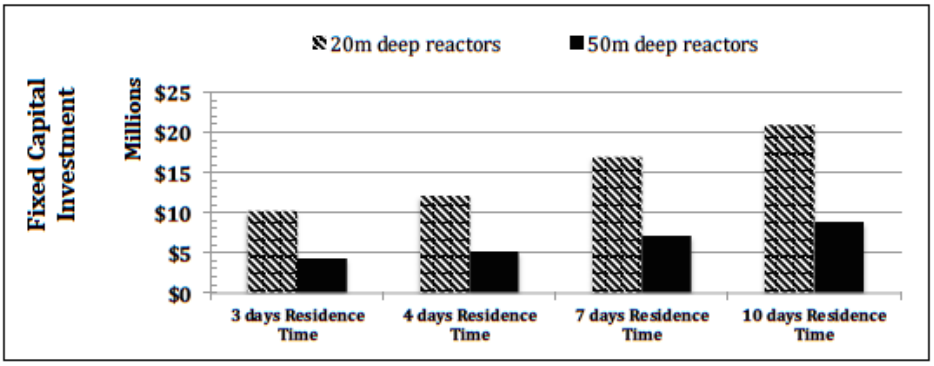


Figure 5. Annual operating cost estimation of different biodrying scenarios, 500 odt/d biomass capacity

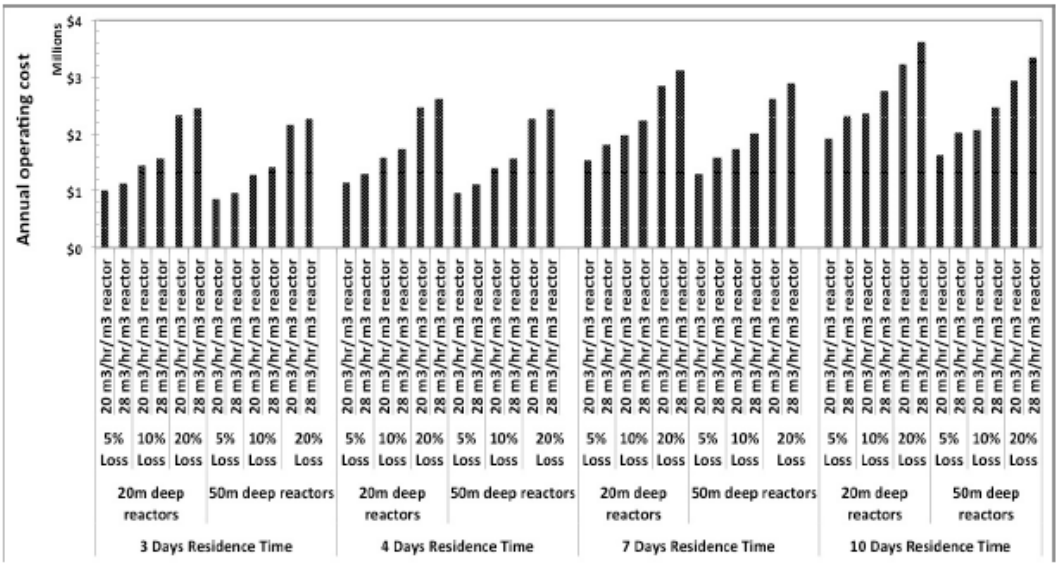
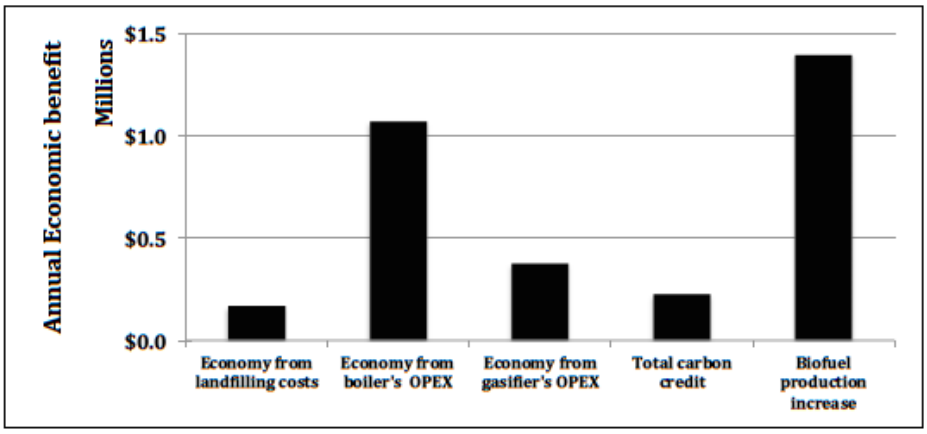


Figure 6. Economic benefits from successful implementation of biodrying system to gasification-based biorefinery process for 500 odt/d biomass capacity



3.2. Profitability evaluation and economic viability

Generally, in the industry, for profitable and successful projects IRR of 20% is targeted. However, in immature and high risk projects such as biorefinery technologies IRR of 30% and higher should be targeted to minimize the risks and stay on the safe side[32]. For economic analysis of biodrying process the following assumptions have been made: 350 operating days per year in the mill, 20 years project lifetime, salvage value of biodryers equal to zero after the lifetime, 100% equity, 30% income tax, and accelerated depreciation

that depreciate the equipment by 50% of the cost in the first year 25% in the second year and 25% in the third year. Such depreciation approach is widely accepted in the industry. Economic evaluations for treating 500 odt/d biomass with 300 kg/m³ bulk density show that 20m deep biodrying units are not among the interesting scenarios due to high fixed capital investment. Profitability assessment reveals that bigger biodrying units and shorter residence times make biodrying process a viable option for the mill in conjunction with gasification process. In Table 10 internal return rate of various biodrying scenarios for bigger units in conjunction with gasification have been listed.

Table 10. IRR of various biodrying scenarios in conjunction with gasification, with and without governmental contributions

Biodrying Scenarios		IRR without government contribution	IRR with 25% government contribution	IRR with 50% government contribution
10 days Residence Time	5% carbon loss 50m deep units 20 m³/hr airflow rate	3%	7%	14%
7 days Residence Time	5% carbon loss 50m deep units 20 m³/hr airflow rate	9%	14%	23%
4 days Residence Time	5% carbon loss 50m deep units 20 m³/hr airflow rate	17%	26%	42%
	5% carbon loss 50m deep units 28 m³/hr airflow rate	19%	24%	39%
	10% carbon loss 50m deep units 20 m³/hr airflow rate	14%	20%	32%
	10% carbon loss 50m deep units 28 m³/hr airflow rate	12%	18%	30%
3 days Residence Time	5% carbon loss 50m deep units 20 m³/hr airflow rate	24%	34%	55%
	5% carbon loss 50m deep units 28 m³/hr airflow rate	23%	32%	51%
	10% carbon loss 50m deep units 20 m³/hr airflow rate	19%	27%	41%
	10% carbon loss 50m deep units 28 m³/hr airflow rate	17%	25%	39%

In 50m deep biodrying units, the internal rate of return without government contributions in ten and seven days residence time for the best scenario are 3% and 9%, respectively, which are far from the acceptable return rate, and if there would be government contribution up to fifty percent of fixed capital investment they rise up to 14% and 23%, respectively, which still have difference from targeted IRR. However, satisfactory return rates are obtained where there would be government contributions on the initial investments. In case of government contribution up to one fourth of fixed capital investment, the acceptable return

rates take place at 3 days residence time if carbon loss of biological aerobic activity inside the reactor does not exceed 5%. Government contribution up to fifty percent of the investment cost extends the acceptable return rate of biodrying technology to 4 days residence time and 10% carbon loss where airflow rate should not exceed 28 m^3/hr per cubic meter of biodrying reactor. In such scenarios IRR are varied between 30-55%. Ten biodrying conditions listed in Table 11 are addressed as biodrying viable conditions in conjunction with gasification-based biorefinery of base case mill.

3.3. Major risk of biodrying viability

The most important condition for viability of biodrying is final dryness level of biomass that must reach to at least 80% at biodrying discharge for acceptable performance of gasifiers. Such dryness level requires removal of unbound and bound water. The significant challenge and major risk of successful biodrying for gasification application is however the treatment and removal of bound water, those who are embedded in the biomass particles' structures. If bound water cannot be removed and final dryness level cannot be attained within the economic retention time, viability of biodrying process will be at risk. The bound water must primarily be brought up to the surface by an intense mechanism then removed by convective air, which is more complicated and needs an engineered process. In order to address the risk, in the second phase of the study experimental test of biomass biodrying on the vertical pilot-scale unit has been accomplished and results will be published.

Table 11. Viable biodrying conditions for gasification-based biorefinery process of base case mill

Condition	Final Biomass Dryness Level	Residence Time	Reactor Depth	Carbon Loss	Airflow Rate per m^3 of reactor	IRR
(1)	> 80%	3 Days	50 m	5%	20 m^3/hr	55%
(2)	> 80%	3 Days	50 m	5%	28 m^3/hr	51%
(3)	> 80%	4 Days	50 m	5%	20 m^3/hr	42%
(4)	> 80%	3 Days	50 m	10%	20 m^3/hr	41%
(5)	> 80%	4 Days	50 m	5%	28 m^3/hr	39%
(6)	> 80%	3 Days	50 m	10%	28 m^3/hr	39%
(7)	> 80%	3 Days	50 m	5%	20 m^3/hr	34%
(8)	> 80%	4 Days	50 m	5%	20 m^3/hr	32%
(9)	> 80%	3 Days	50 m	10%	28 m^3/hr	32%
(10)	> 80%	4 Days	50 m	10%	28 m^3/hr	30%

4. Conclusion

The preliminary techno-economic analysis presented in this paper investigates the economic viability of the continuous biodrying technology that has been developed at École polytechnique de Montréal (Canada), implemented in gasification-based biorefinery process in pulp and paper mills. The study identifies conditions where biodrying can be employed economically in the mill instead of conventional drying technologies. From literature review of gasification technologies it was concluded that final dryness level of biomass is the most important parameter and must reach to higher than 80% before gasification process, therefore it is assumed that biodrying process could make such dryness level within the considered scenarios. Different scenarios were considered including 500 odt/d biomass capacity with 300 kg/m^3 bulk density, 3, 4, 7, 10 days residence time of biomass in the reactors, 20m & 50m deep

reactor designs, 5%, 10%, 20% biological loss due to biological activity of microorganisms, and 20, 28 m^3/hr per each cubic meter of reactor airflow rate. From the results it was concluded that the viable conditions take place where:

- Targeted dryness level is achieved within 4 days and less
- Carbon loss of aerobic biological activity is 10% and less
- Biodrying units have 50m depths

Airflow rate in the range of 20-28 m^3/hr per cubic meter of reactor only changes few percentages of internal rates of return and doesn't have significant effect on the viability of biodrying system. Since the fixed capital investment corresponds to residence time, higher time of retention imposes more initial cost. Among the scenarios seven and ten days residence time make the biodrying system not a suitable option for gasification-based biorefinery process where all the viable conditions take place in 3 and 4 days residence time. Final dryness level at biodryer discharge is the most important parameter for viability of biodrying system in conjunction with gasification and bound water removal is the significant challenge and major risk to reach such dryness level.

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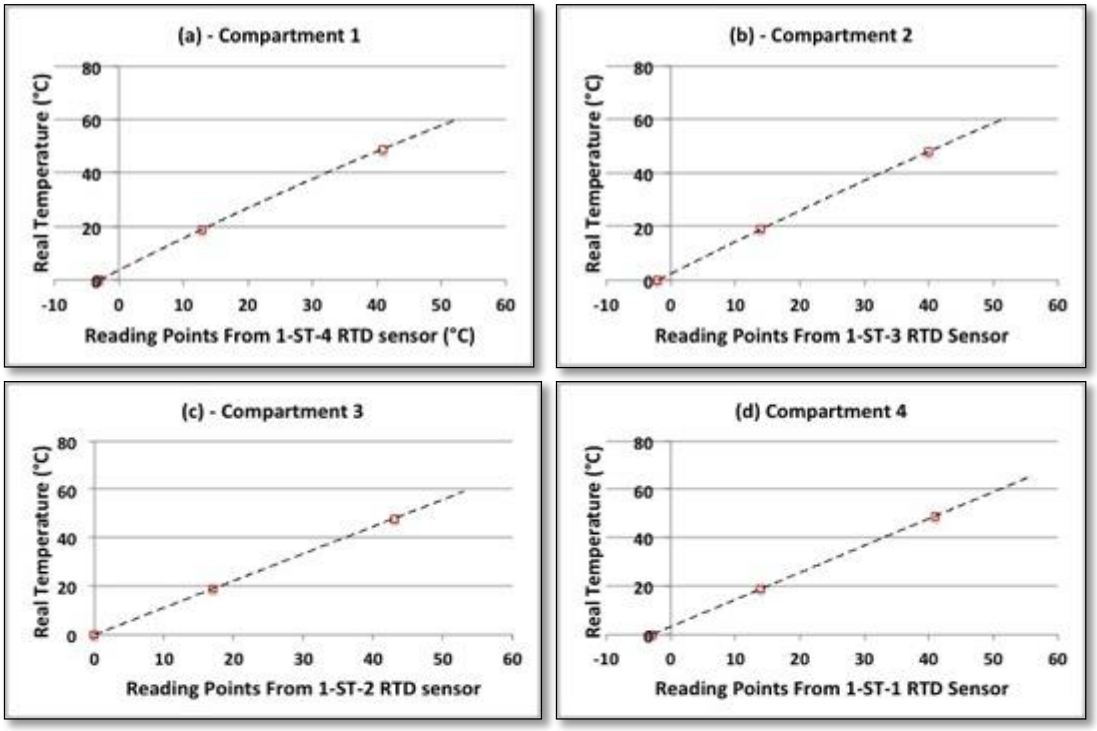
Appendix B. Calibration test values

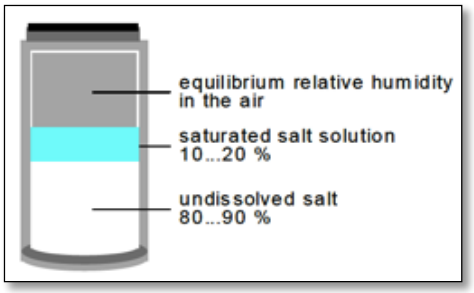
Appendix B.1. RTD sensors & RH probes

For calibrating the sensors, a flask of water is used as temperature bath, with a thermometer as comparison device. Three temperature points are specified: chilled water (mixture of ice & water), water at ambient temperature, and hot water. As a result, the calibration curves have been illustrated to relate the measured value of temperature to the real value.

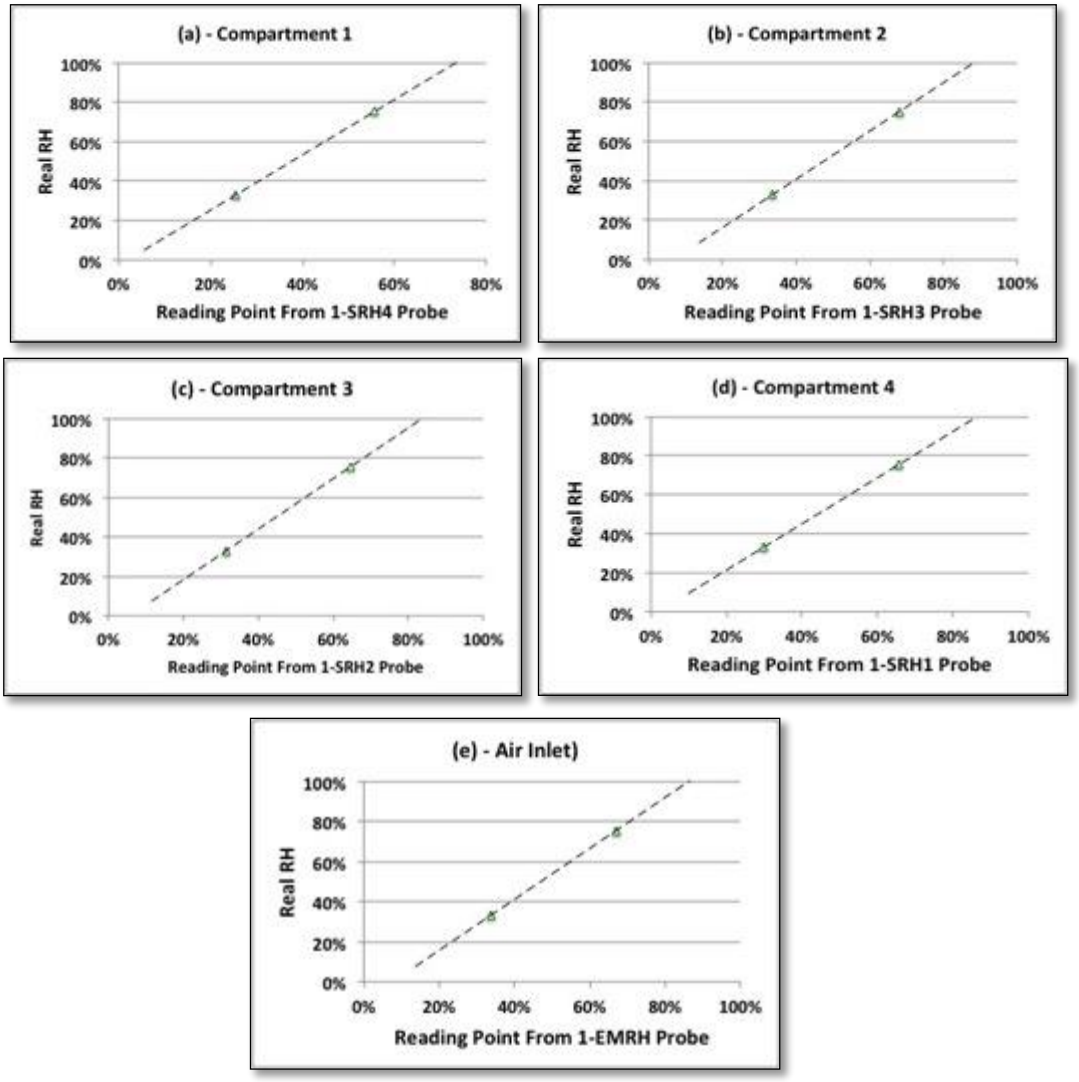


Calibration curves of RTD sensors for: (a) compartment 1 (b) compartment 2 (c) compartment 3 and (d) compartment 4

Lithium chloride (Li-Cl), magnesium chloride ($MgCl_2$), sodium chloride (Na-Cl) and potassium sulfate (K_2SO_4) are typical salts used for RH calibration. They create respectively 11.3%, 33.1%, 75.5%, and 97.6% constant relative humidity at $20^{\circ C}$. Among them, Na-Cl and $MgCl_2$ salts are available in the laboratory and used in the project. Each probe is exposed to the salts for at least 30 minutes.

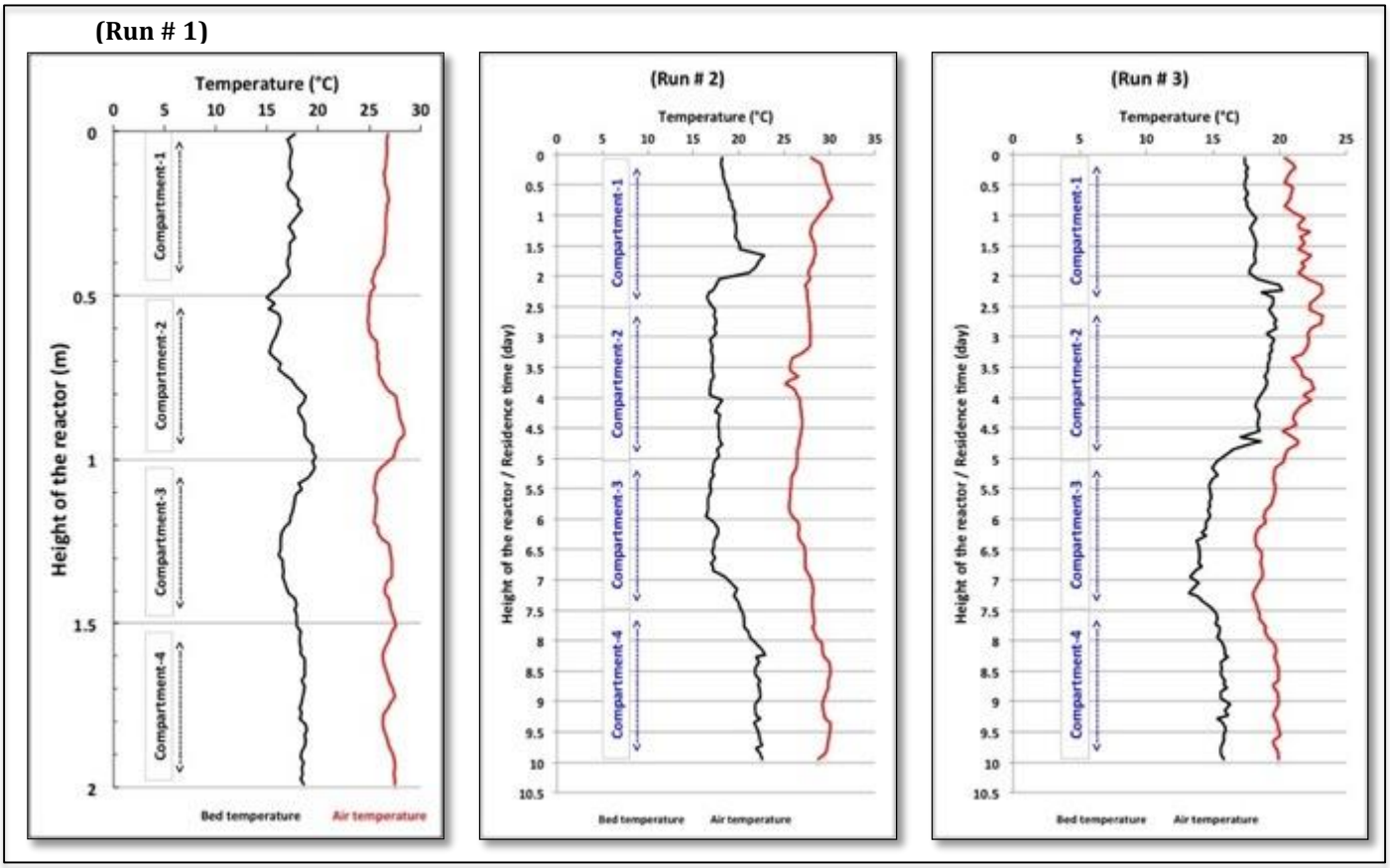


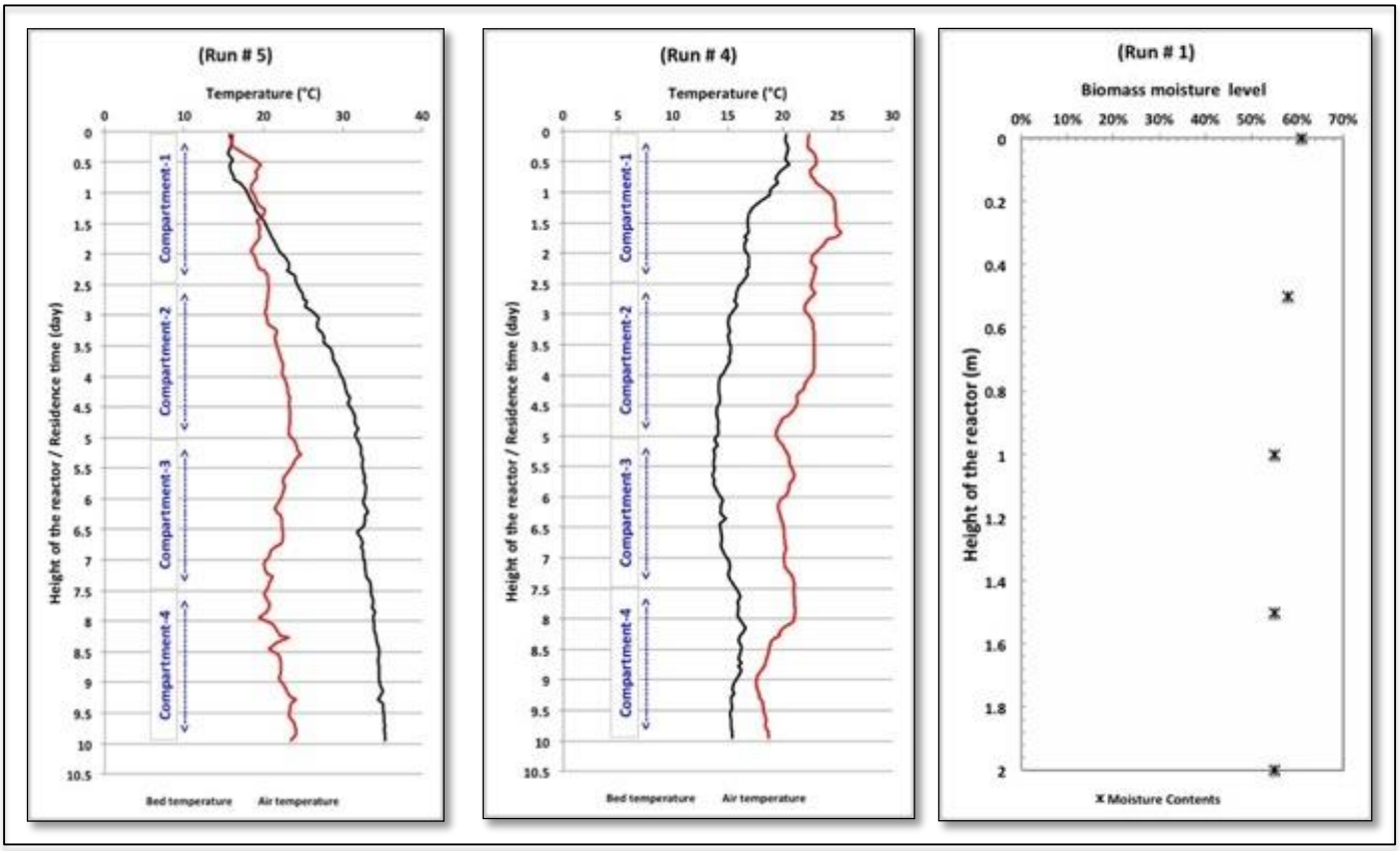
Humidity above the saturated salt in a closed chamber

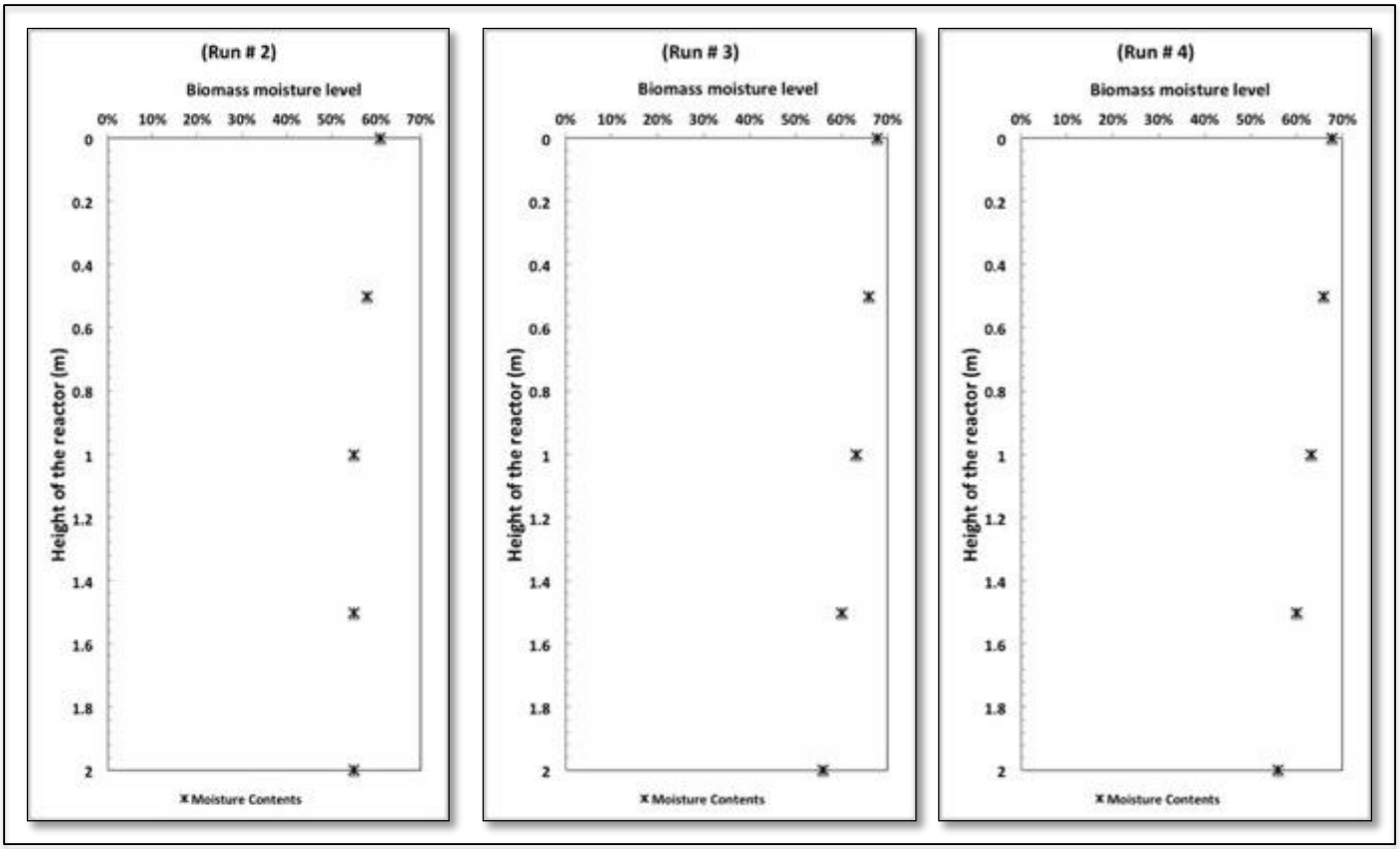


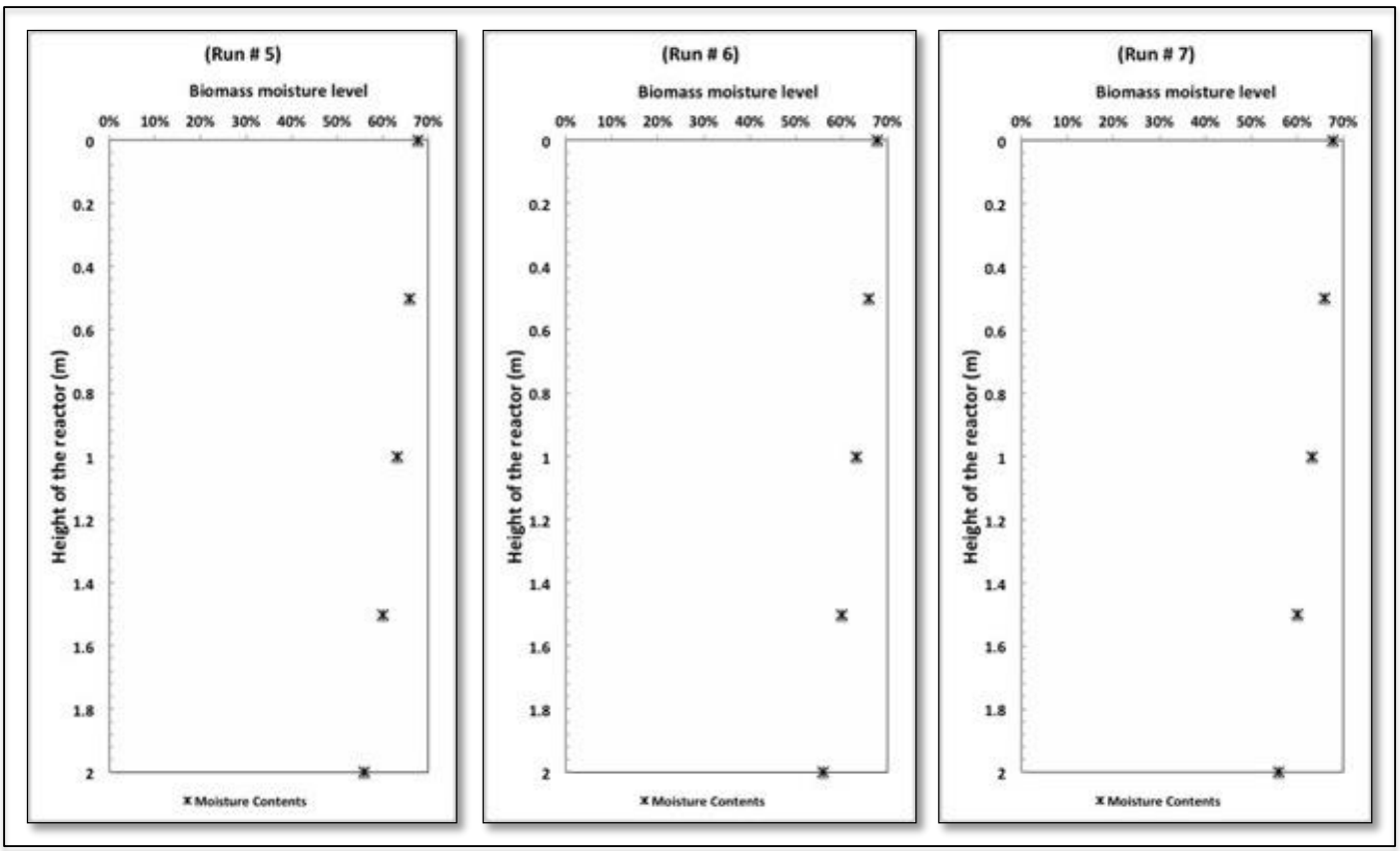
Calibration curves of RH probes for (a) compartment 1 (b) compartment 2 (c) compartment 3 (d) compartment 4 and (e) inlet air

Appendix C. Experiment results- Temperature profile & moisture content along the height of the biodrying reactor






(Run # 2)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents
(Run # 3)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents
(Run # 4)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents


(Run # 5)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents
(Run # 6)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents
(Run # 7)
Biomass moisture level
0% 10% 20% 30% 40% 50% 60% 70%
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Height of the reactor (m)
Moisture Contents